ACQ-PRO

Towards the propagation of AC Quantum Voltage Standards

Workshop on AC Quantum Voltage Standards

PTB, Braunschweig, Germany, June 2015

Collection of training materials

Introduction

This collection of training materials is based on slides presented during *Workshop on AC Quantum Voltage Standards*, held in Physikalisch-Technische Bundesanstalt, June 2015, in the scope of Joint research project ACQ-PRO (14RPT01)

This document can be accessed on the website of the ACQ-PRO project:

`http://www.acqpro.cmi.cz`

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EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Participants of the workshop.

List of topics

1. Josephson basics
2. Josephson Arbitrary Waveform Synthesizer
3. AC Metrology with Josephson Voltage Standards
4. Quantum voltage metrology – instrumentation
5. Cryocoolers in voltage metrology
6. Using a JAWS system inside a cryocooler
7. Practical Training ACQ-PRO

Josephson basics

R. Behr, O. Kieler, S. Bauer, L. Palafox, J. Lee, T. Möhring, J. Kohlmann

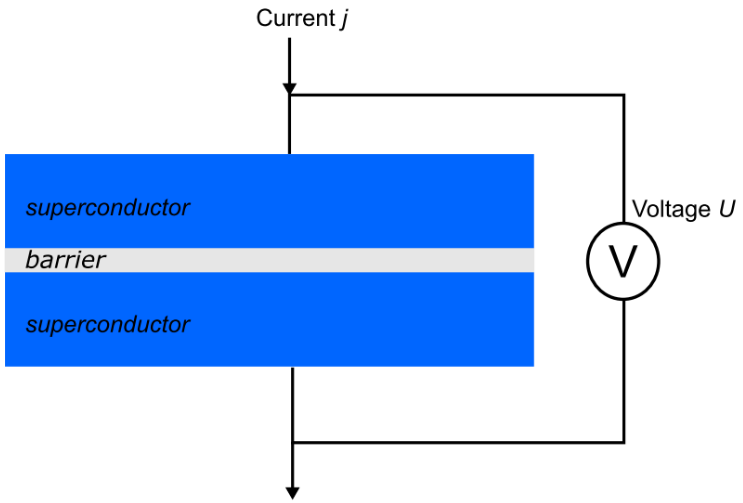
1. Josephson effect, junctions,…
2. Josephson voltage standards
3. Applications
4. Summary and discussion

Josephson effect

The AC Josephson Effect represents a perfect

Frequency to Voltage converter:

$$f_J = (2e/h)\,V = K_J\,V$$



Accordingly a voltage is generated by applying

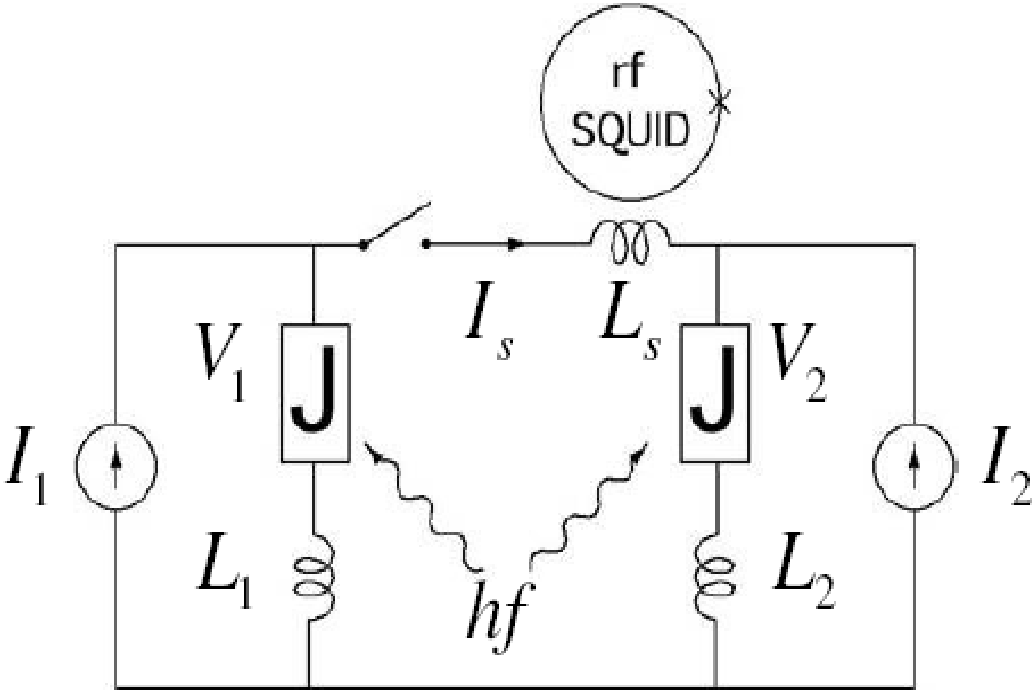
RF to a Josephson junction:

$$V = f_J \cdot \frac{h}{2e} = f_J \cdot K_J^{-1}$$

The value of the Josephson constant was fixed in 1990:

$$K_{J-90} = 483\,597{,}9\ GHz/V$$

How accurate is the Josephson relation?



$$I_s = \frac{1}{L}\int (V_1 - V_2)dt$$

$$L = L_s + L_1 + L_2$$

Very sensitive method!

$\Delta V = V_1 - V_2 = L\, dI_s/dt$

Typically $L \approx 1$ nH - µH, I_s is in the range of nA and $t \approx 1000$ s

Josephson effect: Accuracy

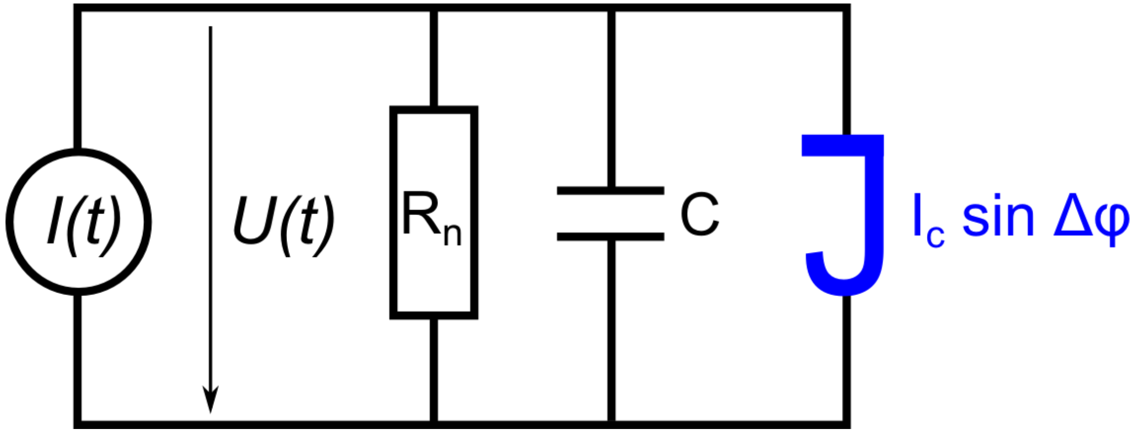
- 1968: ac Josephson effect - $2e / h$ is identical in lead, tin, and indium : $\Delta V / V < 1 \times 10^{-8}$
  J. Clarke, *Phys. Rev. Lett. 21*, 1566-1569, (1968).
- 1983: Comparison between two single junctions: $\Delta V / V < 2 \times 10^{-16}$
  J.S Tsai, A.K. Jain, J.E. Lukens, *Phys. Rev. Lett. 51*, 316, (1983).
- 1986: Comparison between two 1V arrays: $\Delta V_{step} / V_{step}$ (30µA) $< 7 \times 10^{-13}$
  J. Niemeyer et al., *IEEE Electron Device Lett. EDL-7*, 44, (1986).
- 1987: Comparison between two 1V arrays: $\Delta V / V < 2 \times 10^{-17}$
  R.L. Kautz, F.L. Lloyd, *Appl. Phys. Lett. 51*, 2043, (1987).
- 1987: Comparison between two single junctions: $\Delta V / V < 3 \times 10^{-19}$
  A.K. Jain, J.E. Lukens, J.S. Tsai, *Phys. Rev. Lett. 58*, 1165, (1987).
- 2001: Comparison between two 0.6V SINIS arrays: $\Delta V / V < 1.2 \times 10^{-17}$
  I.Y. Krasnopolin, R. Behr, J. Niemeyer, *Supercond. Sci. Technol. 15*, 1034, (2001).

Josephson effect

RCSJ model (Stewart and McCumber) to describe a resistively and capacitive shunted Josephson junction

McCumber Parameter:

$$\beta_C = \frac{2e}{h} \cdot I_C \cdot R_n^2 \cdot C$$



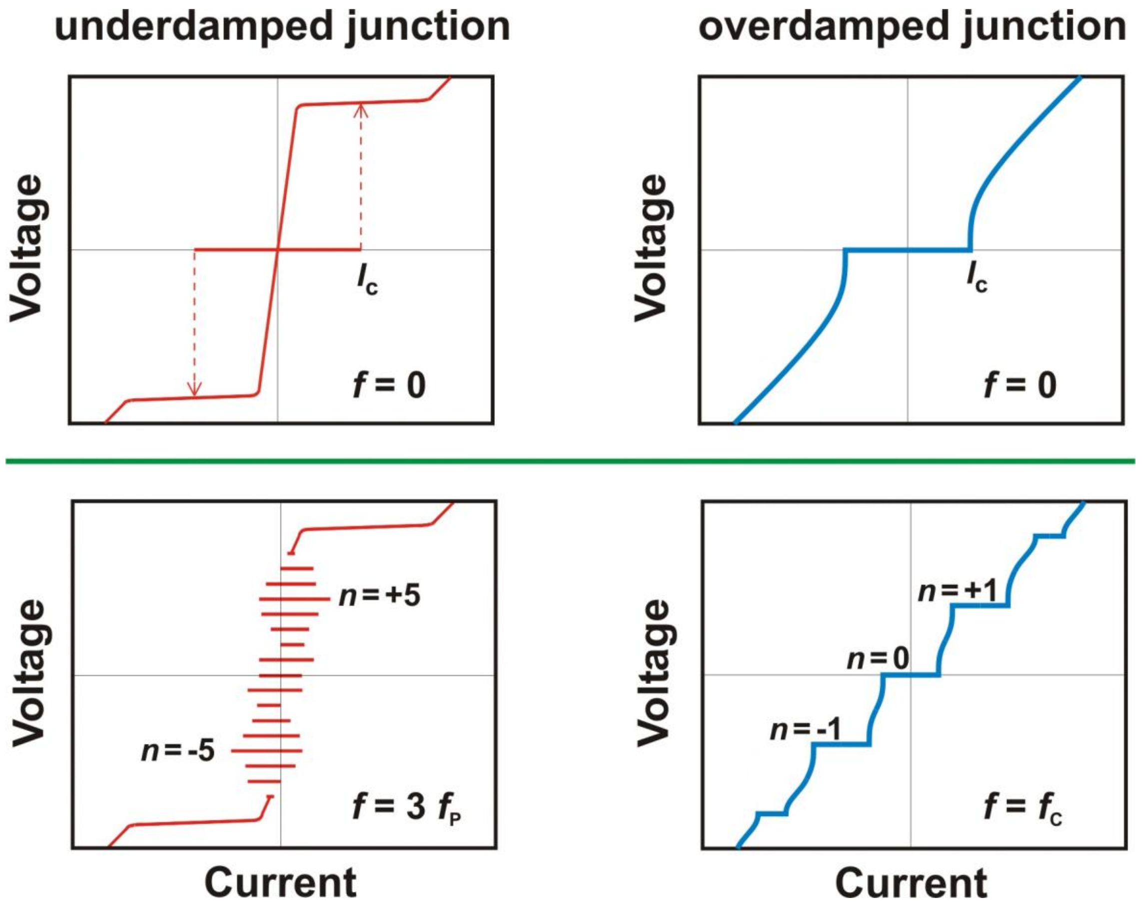
By applying a undulated voltage $V(t) = V + V\cos(\omega t)$ steps of constant voltage develop at which all current is carried by cooper pairs (Shapiro steps)

$$V_n = n \cdot f_J \cdot K_J \quad (n = 0, \pm 1, \pm 2, ...)$$

Josephson effect

$\beta_C >> 1$ → R & C very high (underdamped) → hysteretic behavior (SIS)

$\beta_C \leq 1$ → small C & R (overdamped) → no hysteretic behavior (SNS)



Motivation

Typical uncertainty of a Josephson voltage standard

- at DC (i.e. at 10 mHz) is **10^{-10}** !!

- Typical uncertainty of an AC standard is in the range of **10^{-7}**

- How to make an AC voltage standard?

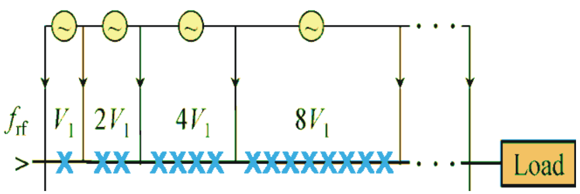
$$V = M N f \Phi_0$$

PJVS and JAWS: principle

AC-Programmable Josephson Voltage Standard	**Josephson Arbitrary Waveform Synthesizer**
70 GHz	15 GHz

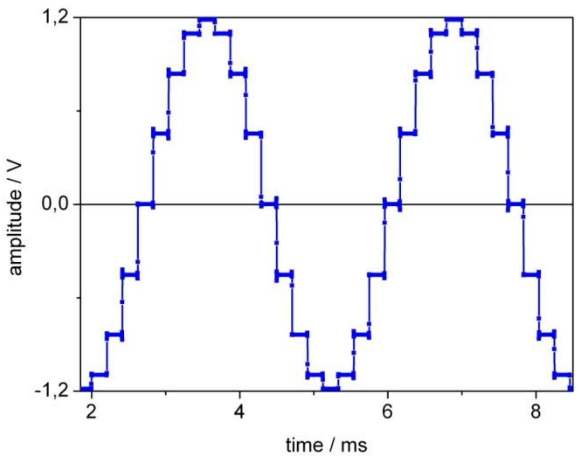
$$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f$$

binary



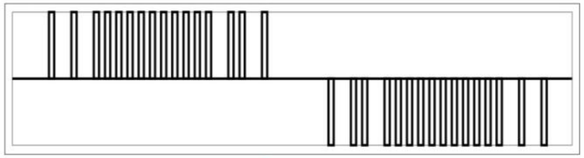
M(t)

number Josephson junctions

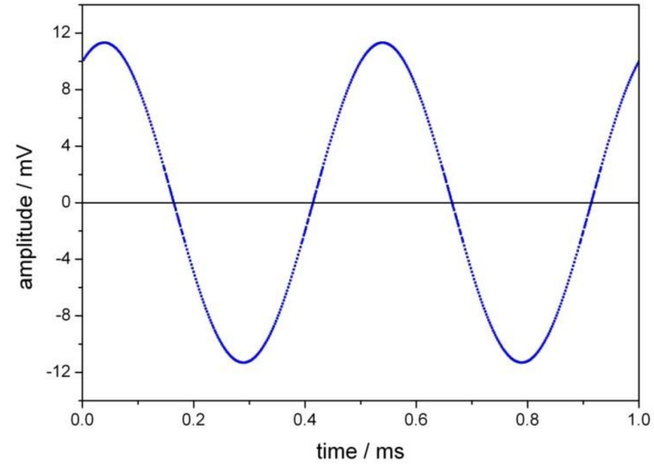


$f_p(t)$

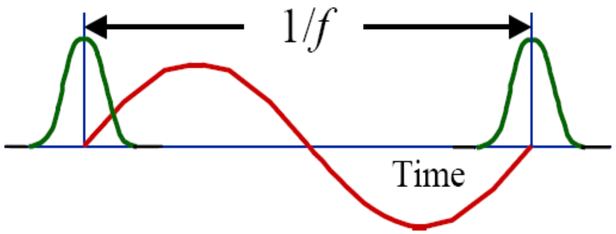
pulse operation

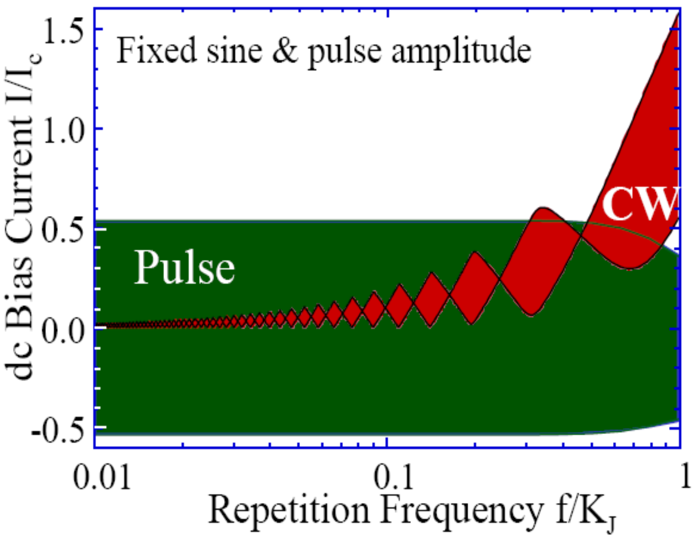


pulse repetition frequency



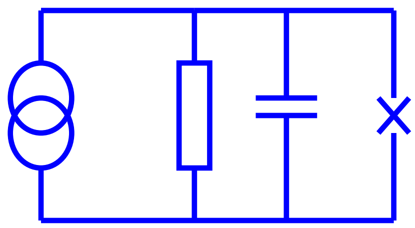
Frequency modulation? $V = n\, f\, \Phi_0$



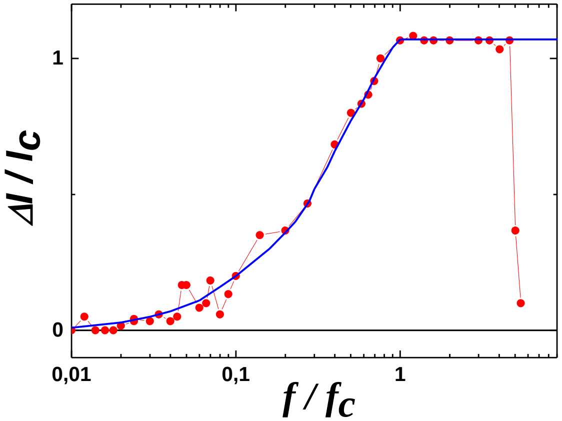


- Continuous Sine Drive
  - No operating margins!
- Pulse Drive
  - Voltage still proportional to frequency
  - Nearly constant margins!

RCSJ – model for JJ



measurement



R. Monaco, *J. Appl. Phys.* 68 (1990) 679
S.P. Benz and C.A. Hamilton, *Appl. Phys. Lett.* 68 (1996) 3171

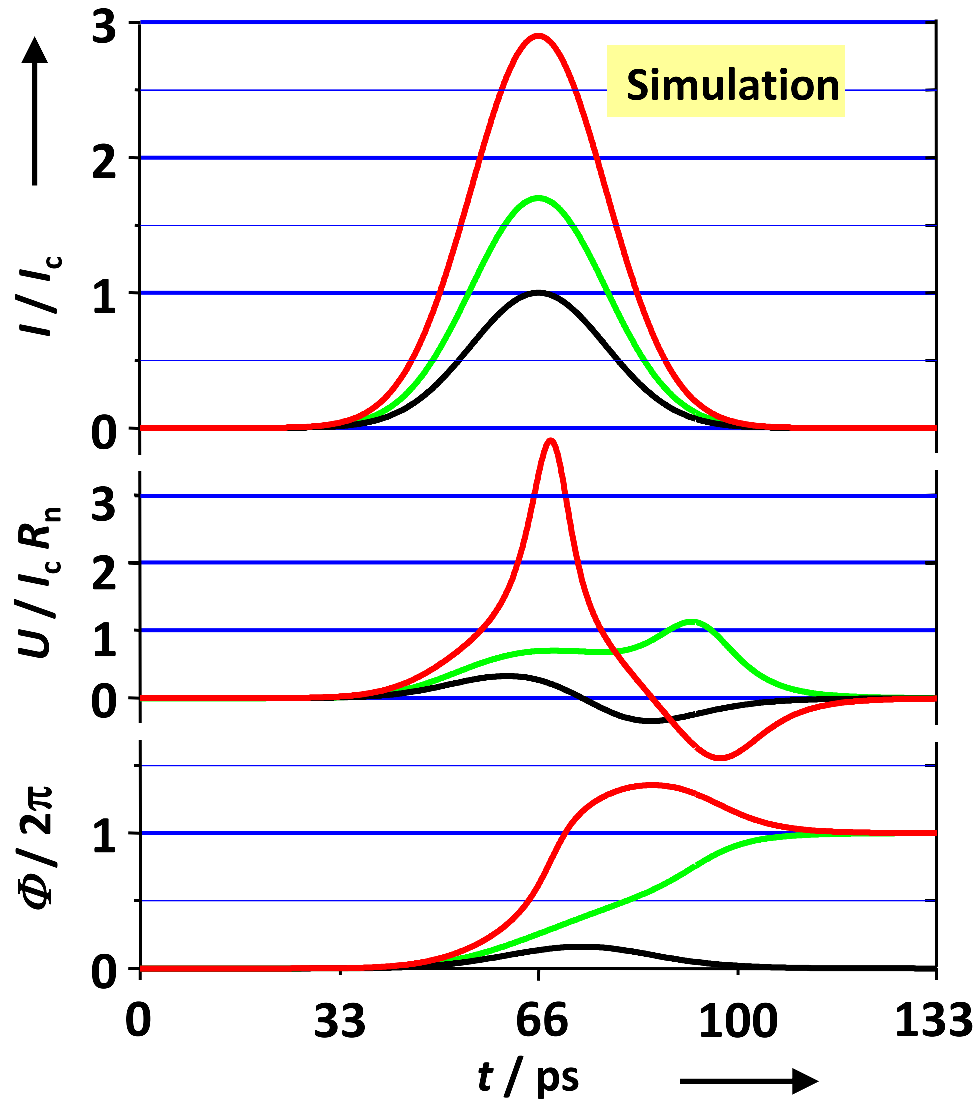
Pulse quantisation

A current pulse is passed through a Josephson junction.

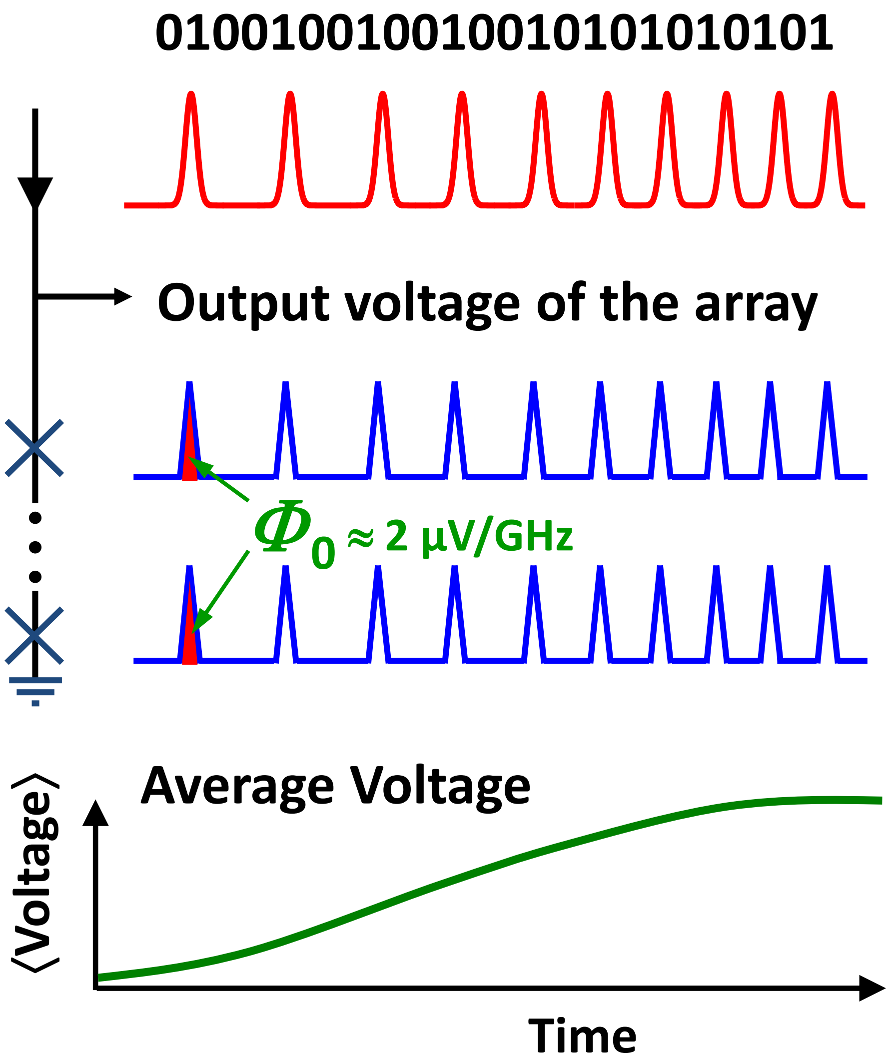
The junction responds by producing a voltage pulse.

The time integral of the voltage pulse is quantised:

$$\int V dt = \pm \frac{n}{K_J}$$



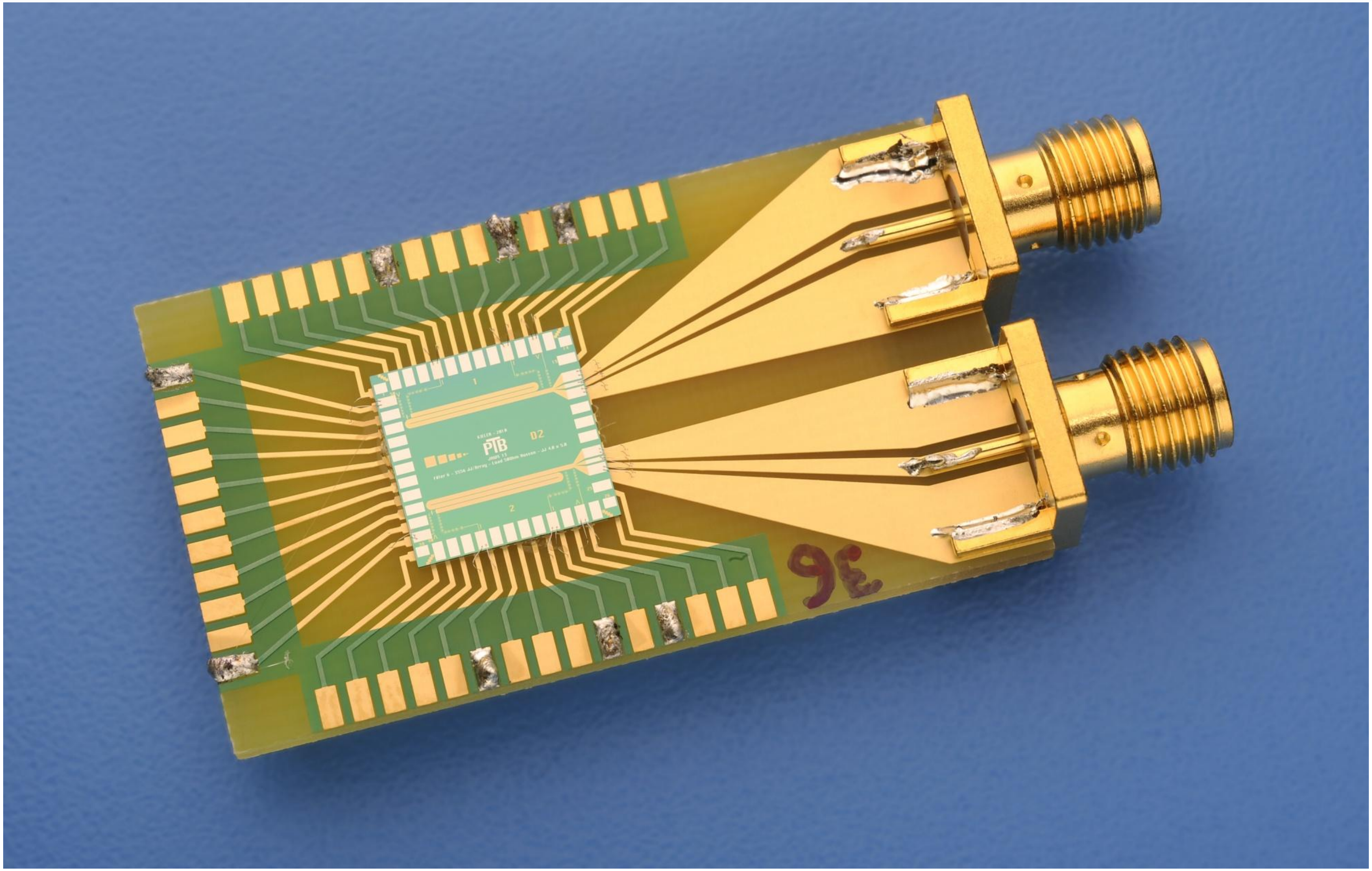
Pulse operation



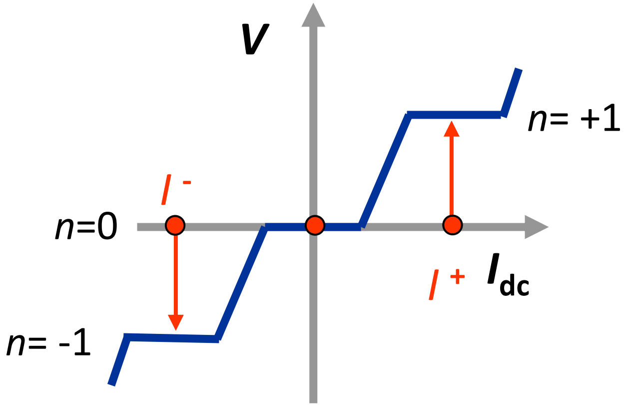
- Fast Code generator (10 GHz repetition frequency)
- Sequence of input pulses determines output voltage
- Quantised voltage pulses by Josephson junctions
- Increasing of the output voltage by series array
- Positive and negative pulses for bipolar voltages

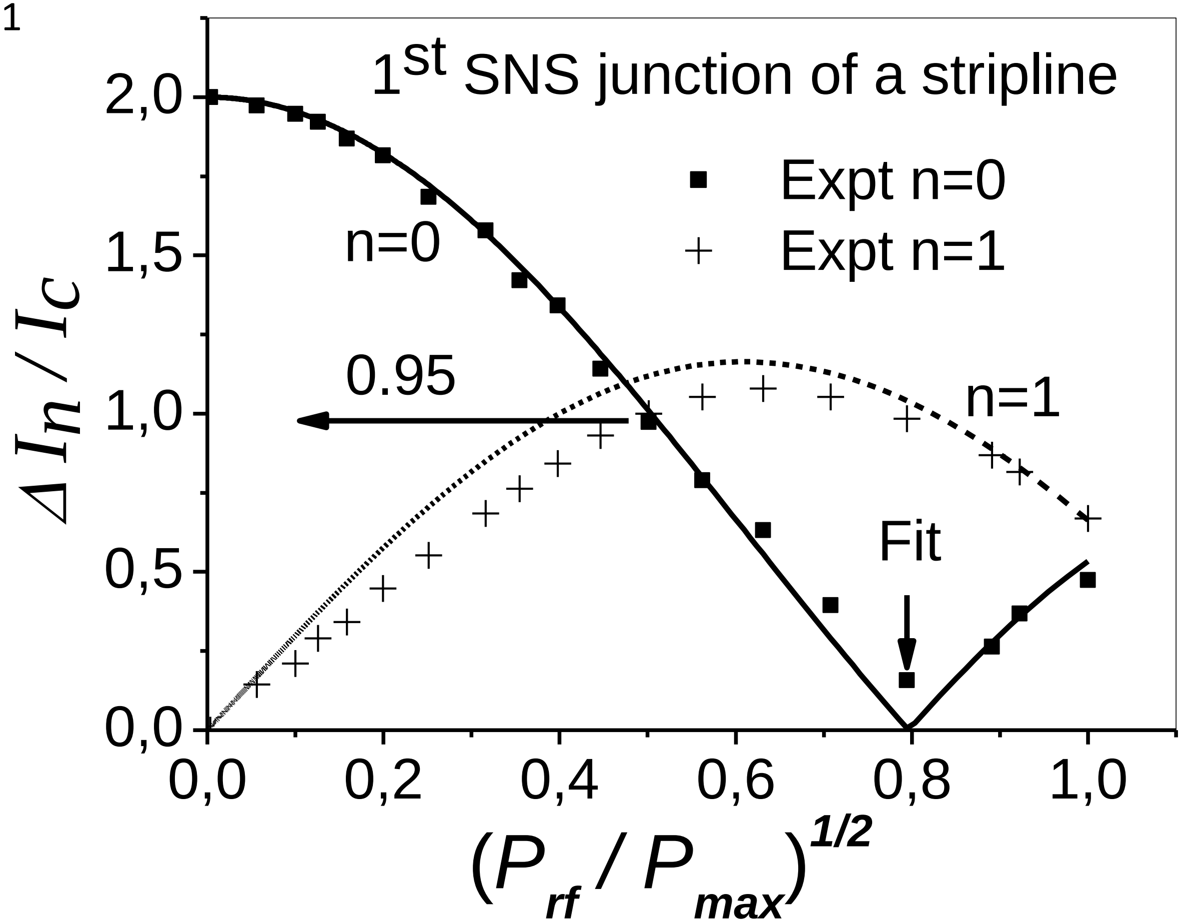
(After S. Benz *et al.*)

JAWS



Microwave power

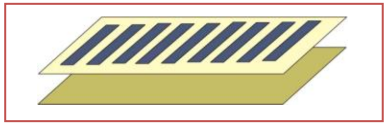




Microwave distribution in Junction series arrays

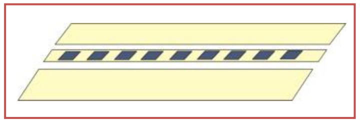
For arrays of underdamped and overdamped junctions three types of striplines are in use:

Microstripline
PTB for SNS
NIST, AIST, PTB,
HYPRES for conv. SIS



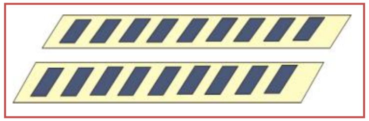
Characteristic impedance 5 Ω
No ground connection
Difficult to match to external waveguides

Coplanar waveguide (CPW)
NIST, AIST, PTB for SNS
VTT/MIKES for shunt. SIS

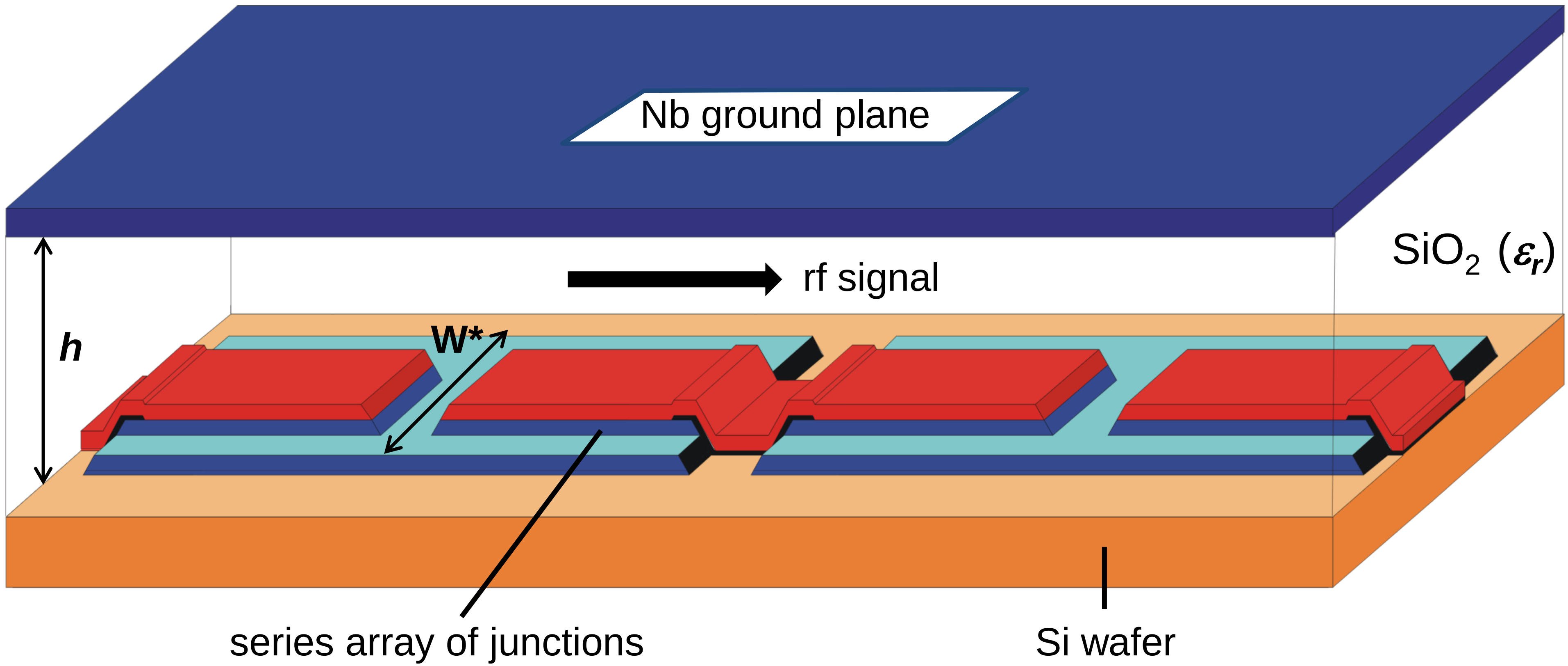


Characteristic impedance 50 Ω
Large mismatch to junctions
Easy to connect to a coaxial 50 Ω cable
Space consuming (junction stacking)
Ground connection

Coplanar stripline (CPS)
IPHT for SINIS and SNS

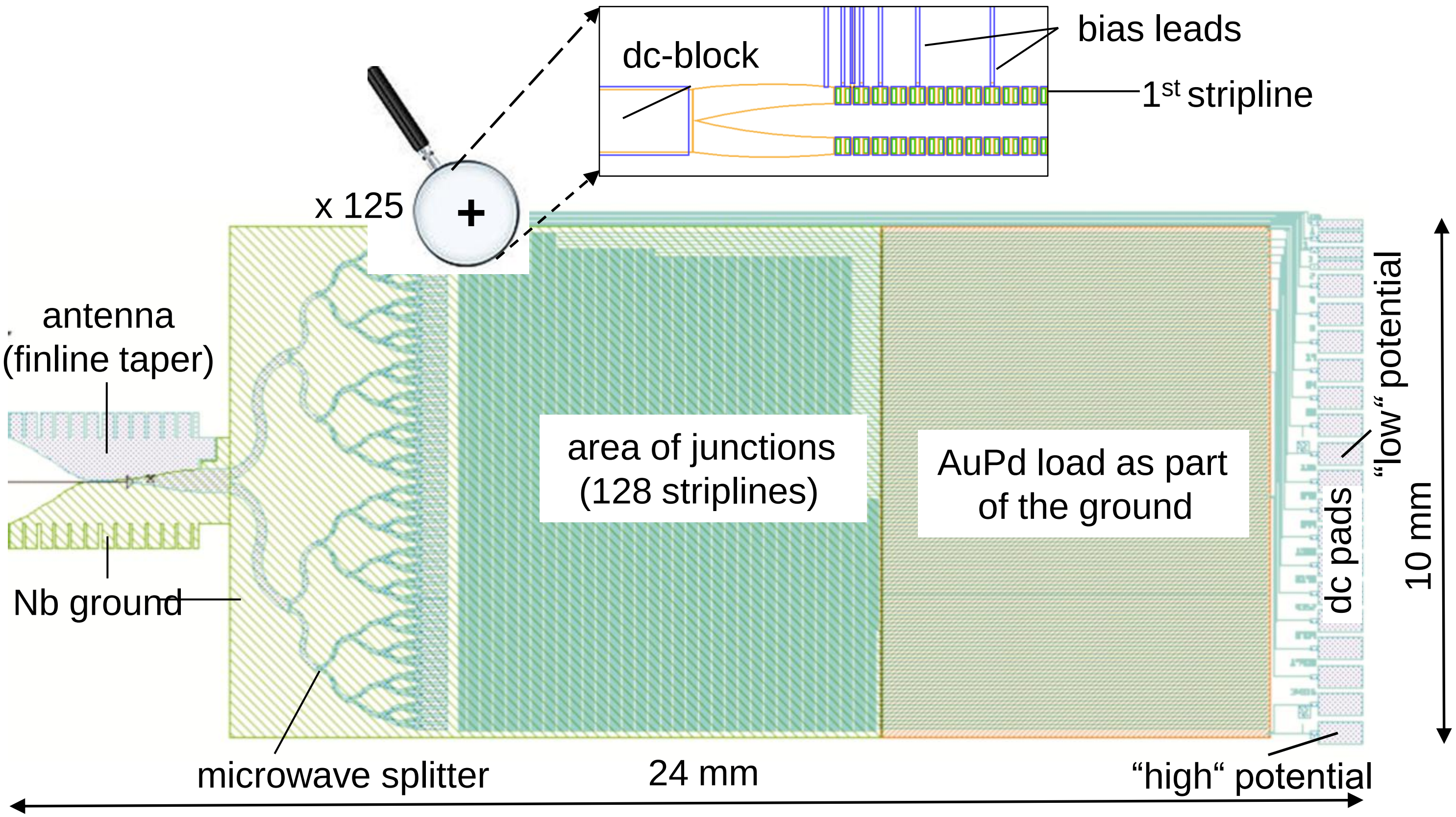


Microwave stripline



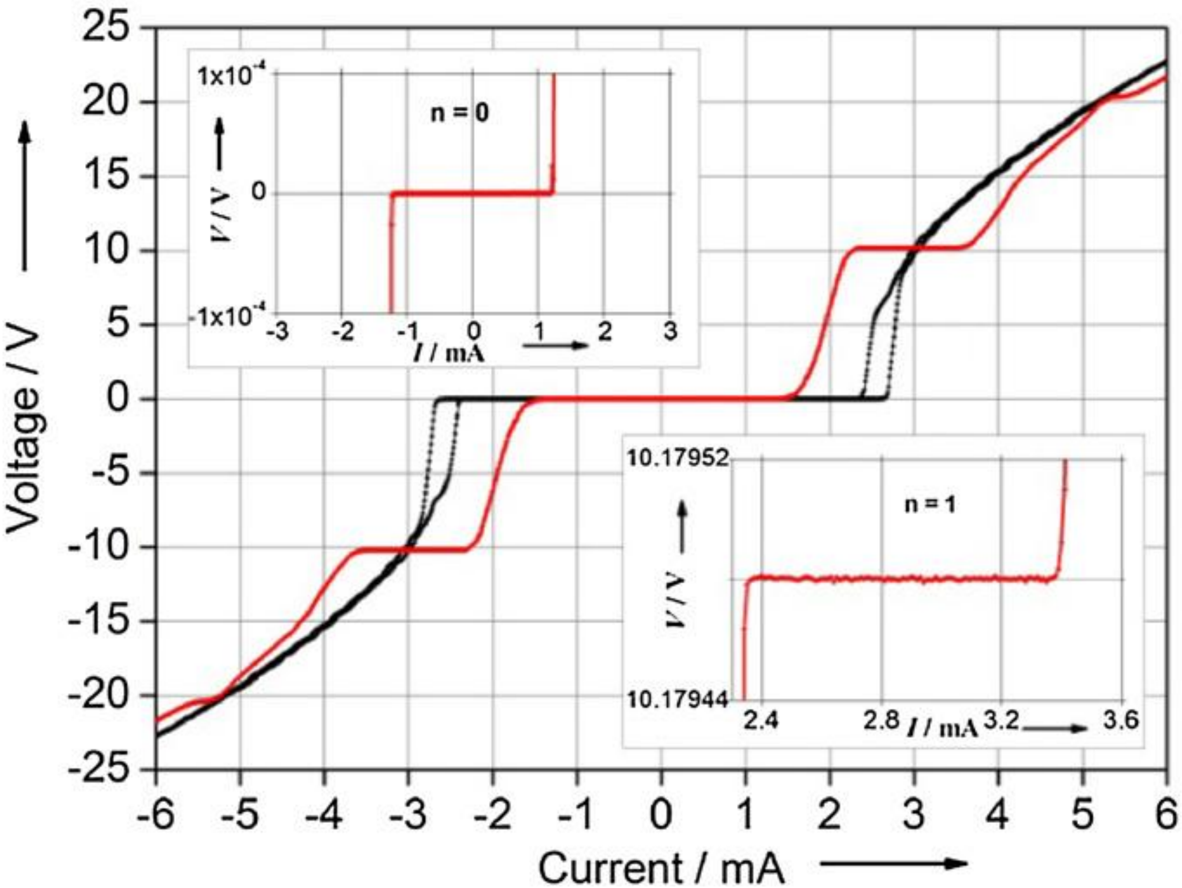
impedance of microstripline: $Z \approx 120\, \pi\, h \,/\, (\varepsilon_r^{0.5}\, w^*)$ [Ω]

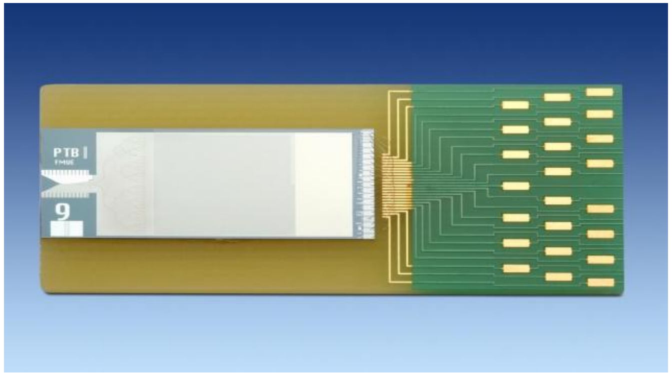
Programmable 10 V array design



69 632 JJs are embedded in 128 striplines connected in parallel
Sequence – 34816 / 17408 / 8704 / 4352 / 2176 / 1088 / 544 / 272 / 136 / 1 / 1 / 1 / 2 / 4 / 8 / 17 / 34 / 68

10 V SNS junction series array



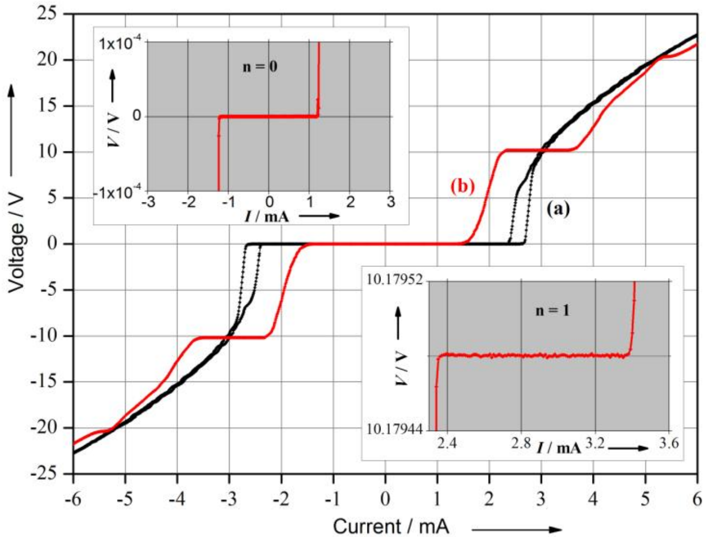


cooperation :
NIST : Nb_xSi_{1-x}
PTB : Design & Technology

2008 worldwide first
10V SNS @ 70 GHz

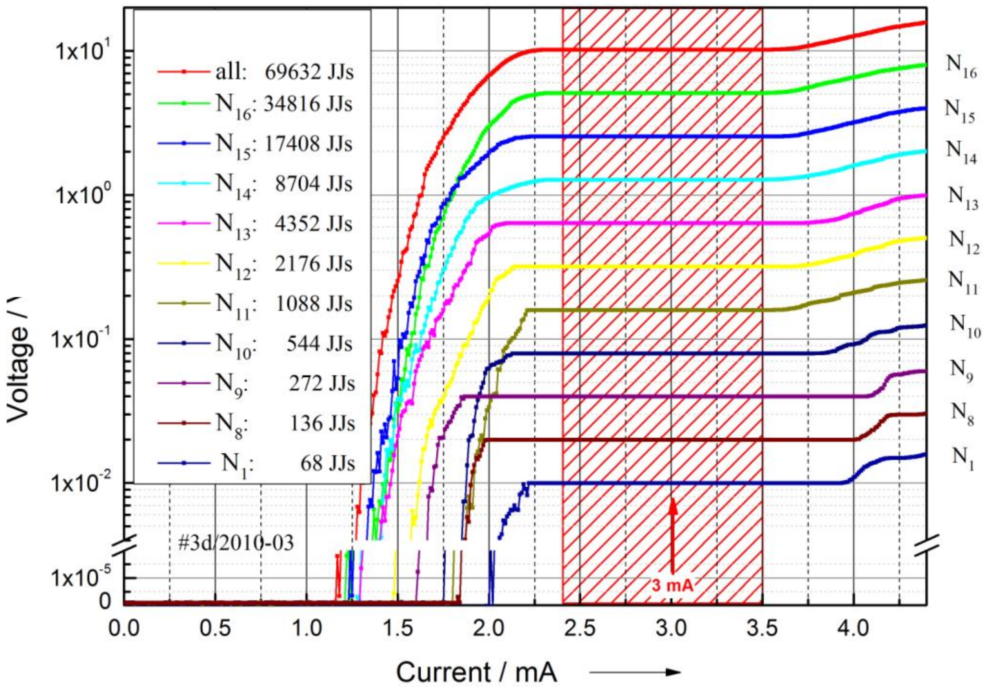
improved performance and higher yield compared to SINIS circuits
no missing JJs!

10 V SNS junction series array - margins

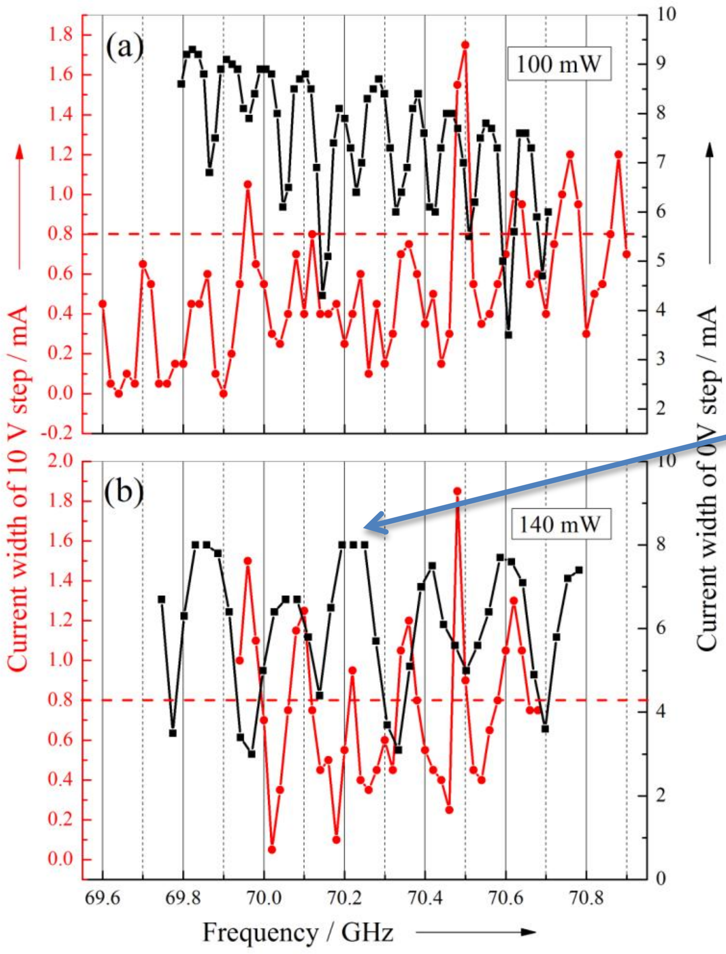


complete array

All steps and segments of the array must have margins!



10 V SNS junction series array - margins

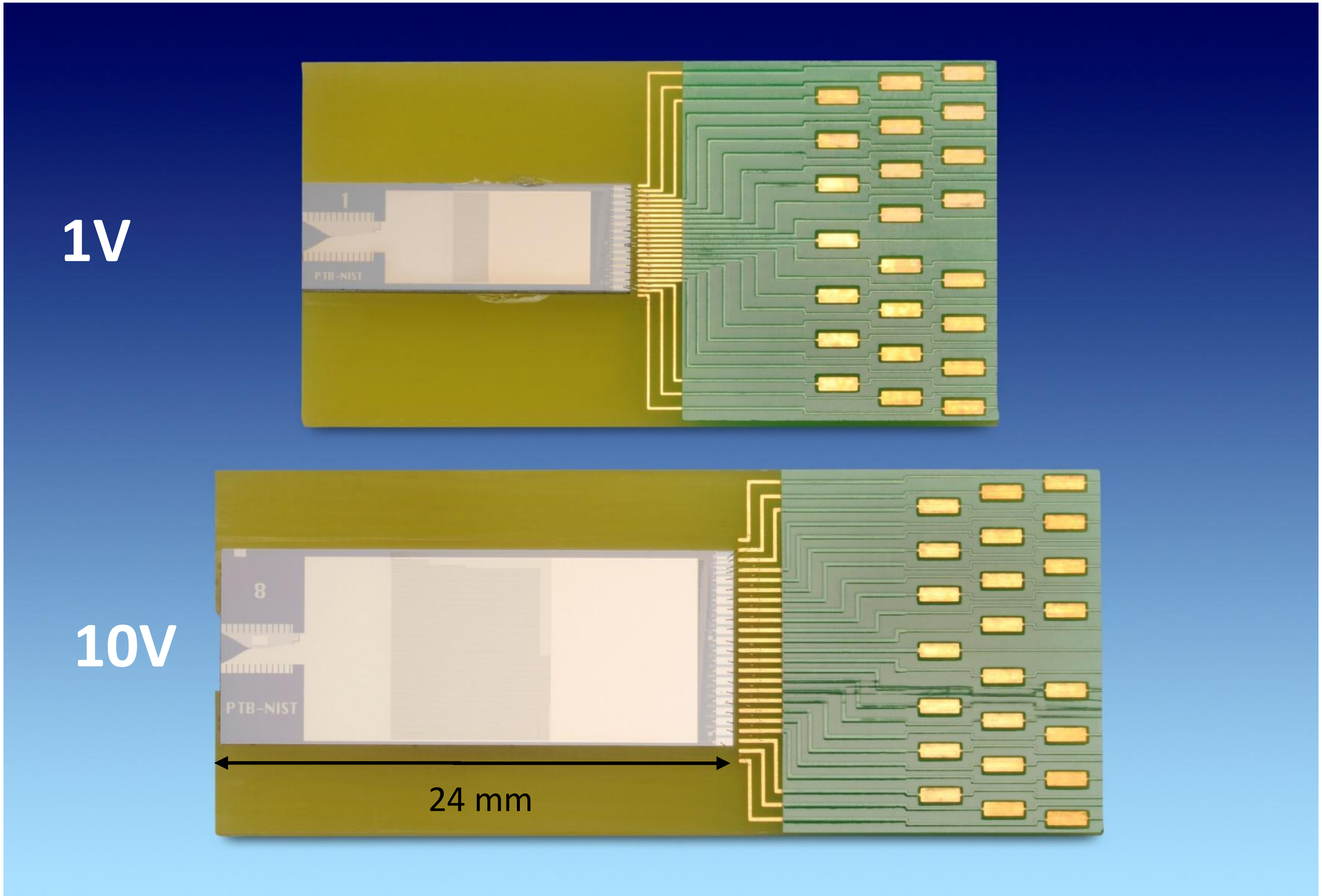


Margins of the array as function of the frequency…

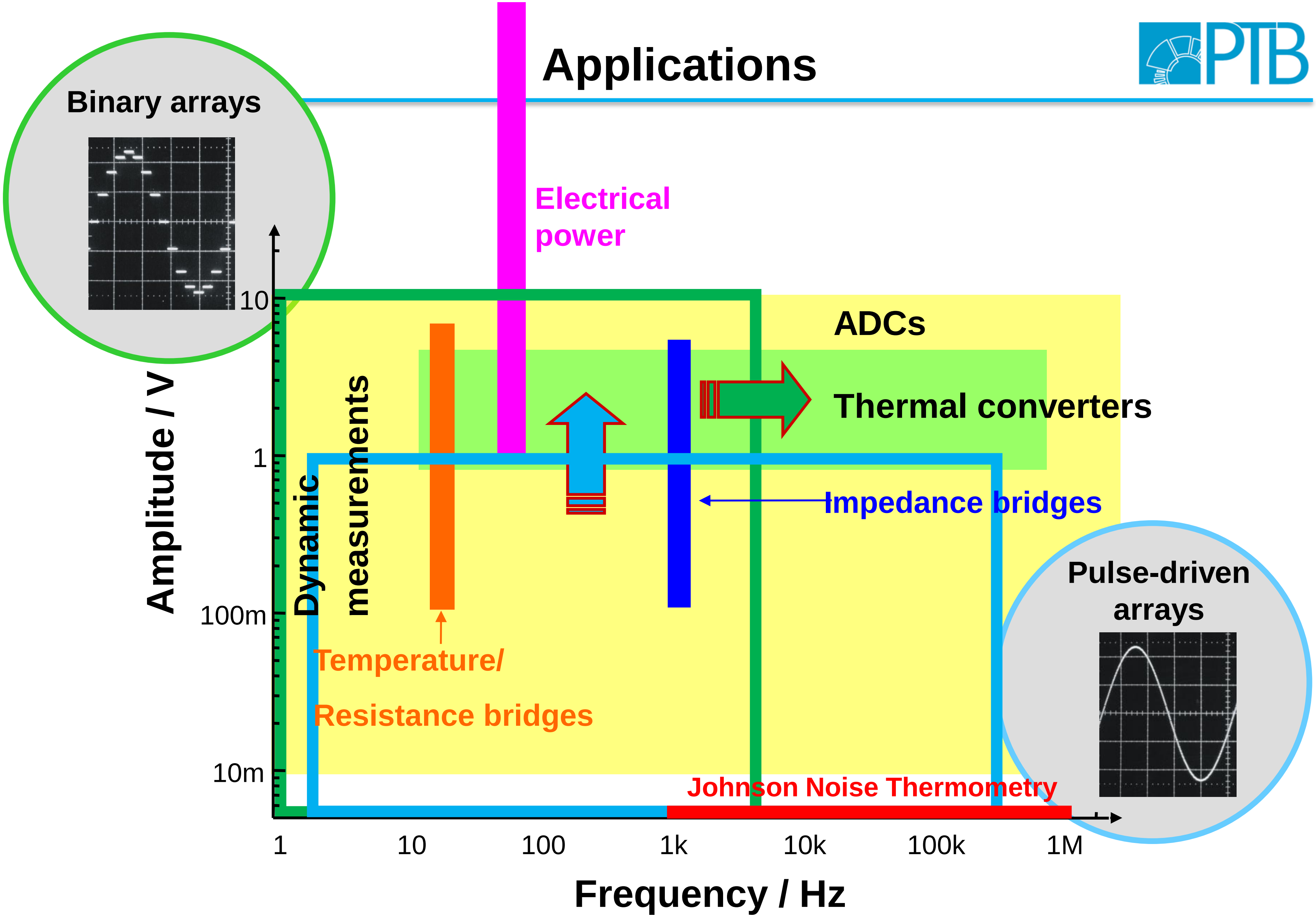
Every array is an individual!

Choose a frequency which allows adjustment with little variation of margins!

Photos programmable SNS Arrays

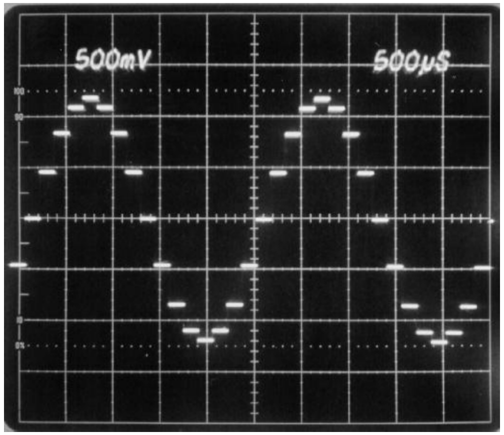


Applications



Linking ac voltage and Josephson standards

Waveform synthesis

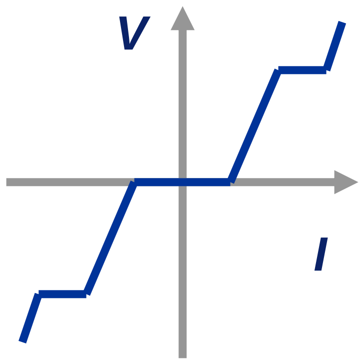


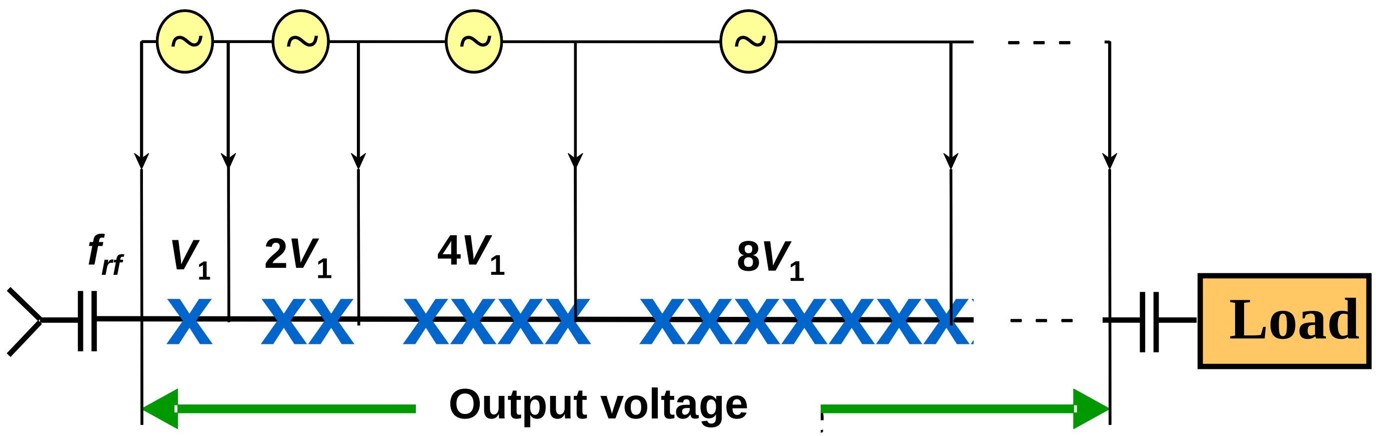
Waveform measurement

Frequency, Transients, Bandwidth, …

Josephson waveform synthesizer

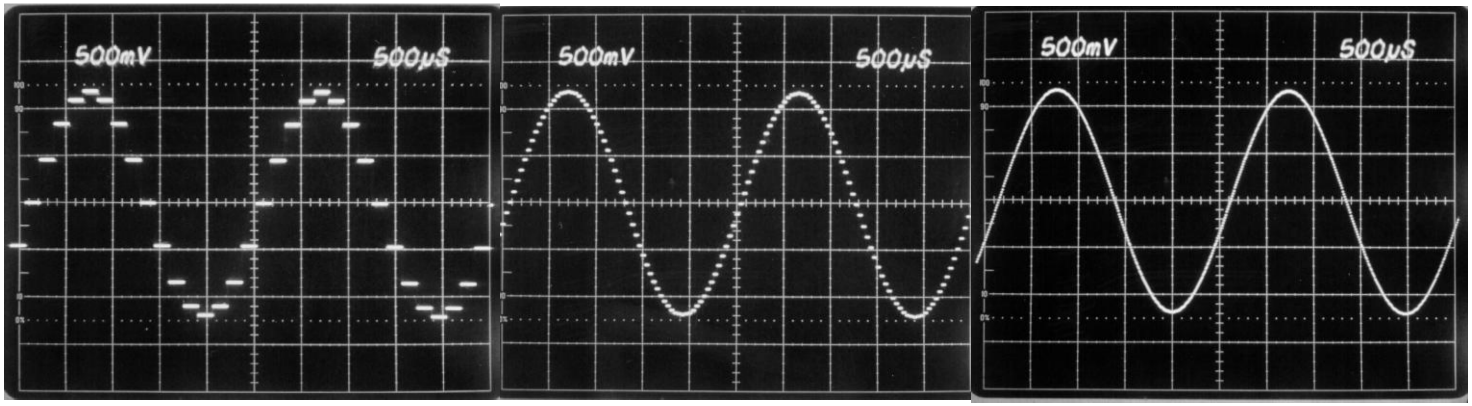
D/A converter





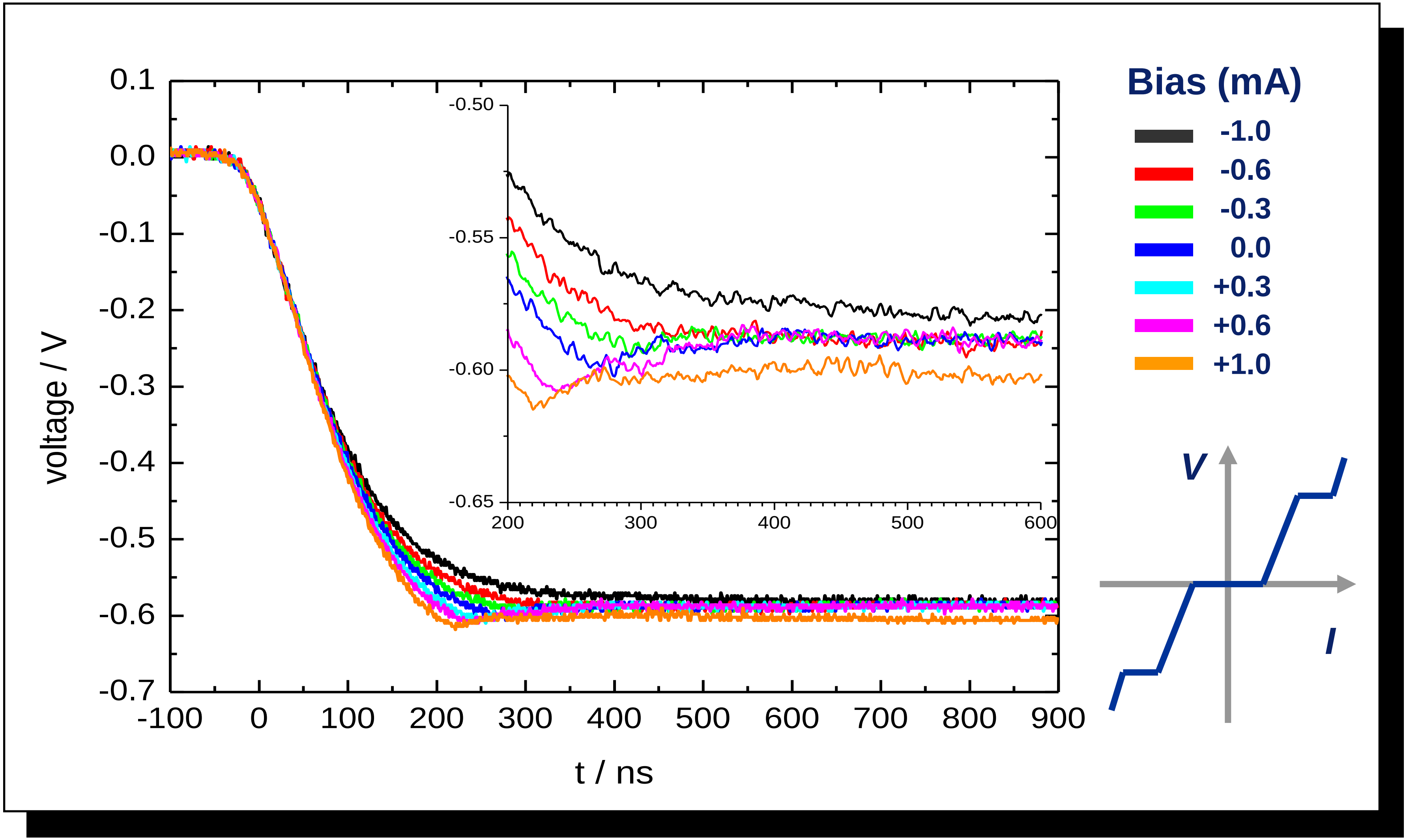
C. A. Hamilton et al., *IEEE Trans. Instrum. Meas. 44 (1995) 223*

- 400 Hz, 13 binary bits



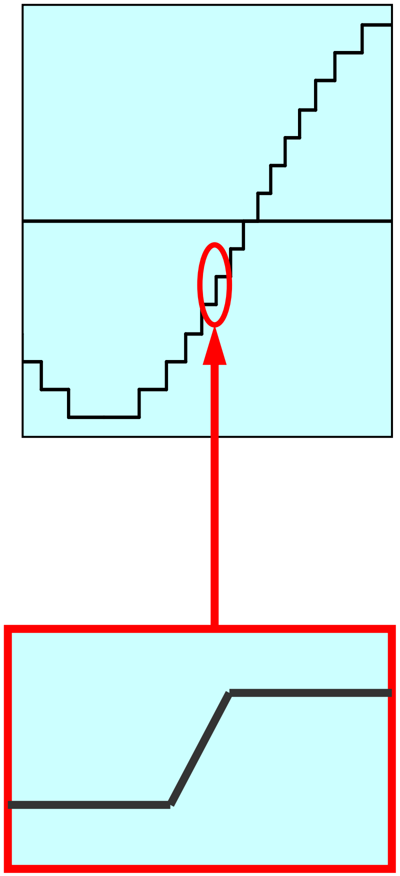
16 samples 64 samples 256 samples

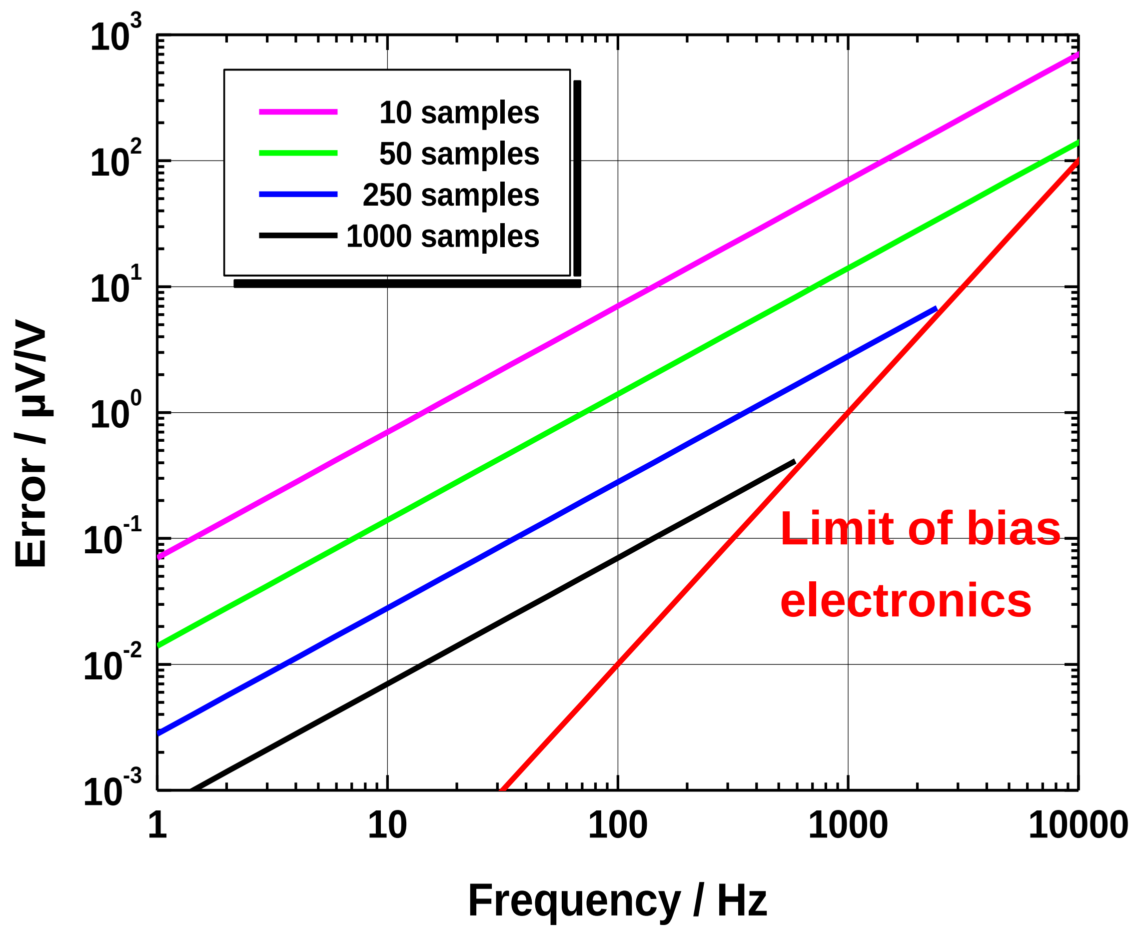
Risetime analysis



Effect of finite risetime

Assuming a linear rise between the quantised values with 250 ns risetime

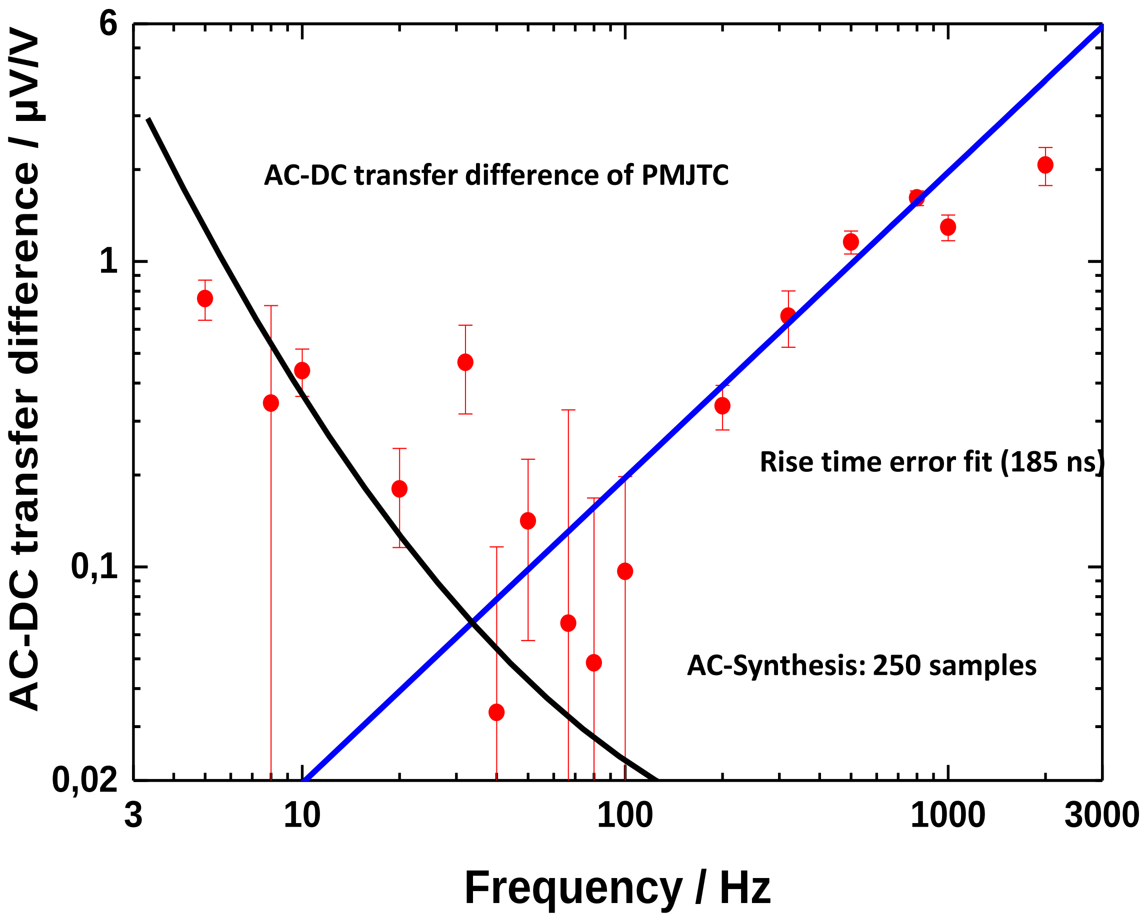




$E \sim (16\, t_r) / (6\, N\, t_w) \sim f$

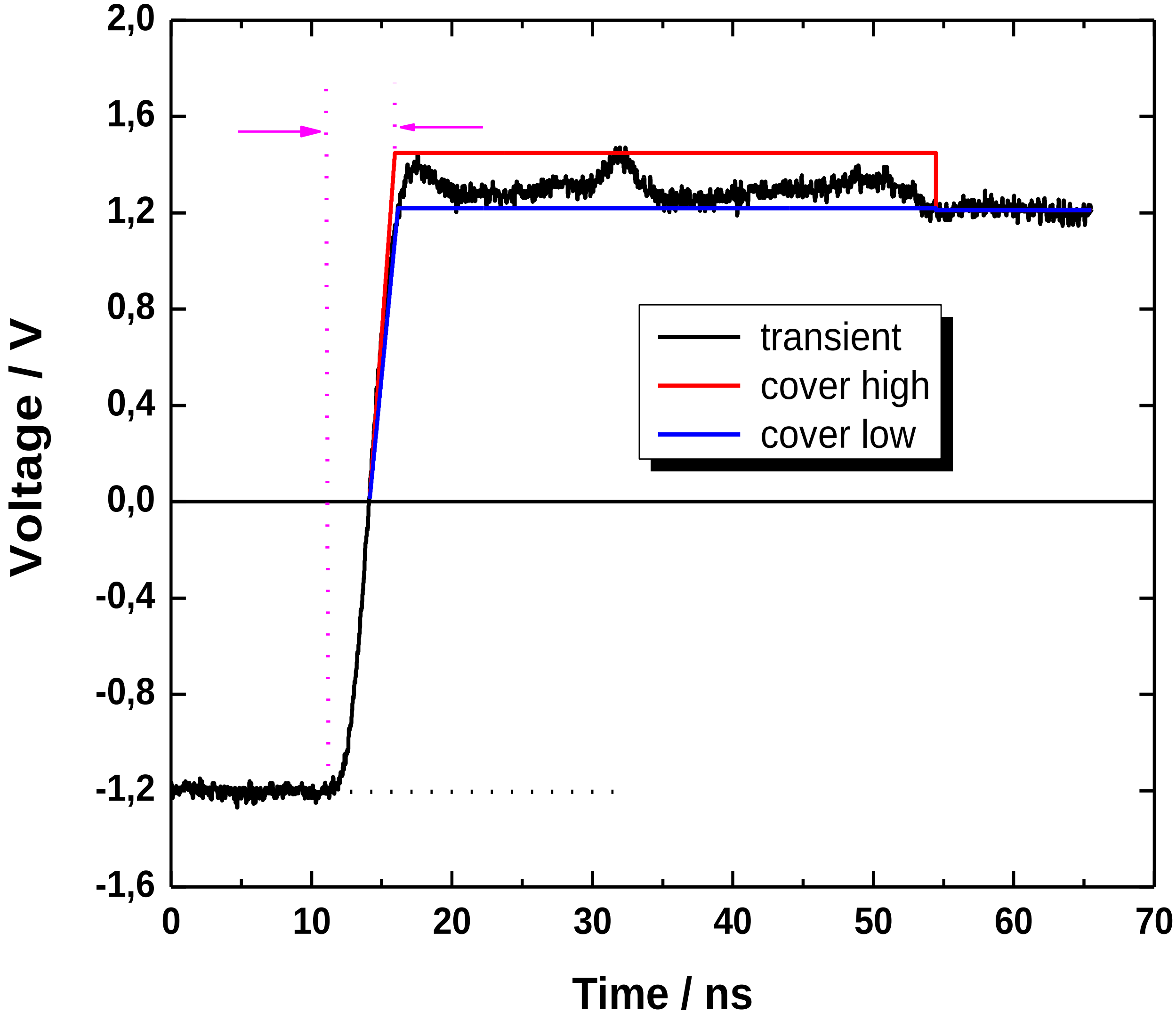
Measurement Results

Planar Multi Junction Thermal Converter with 1025 Ω heater resistance



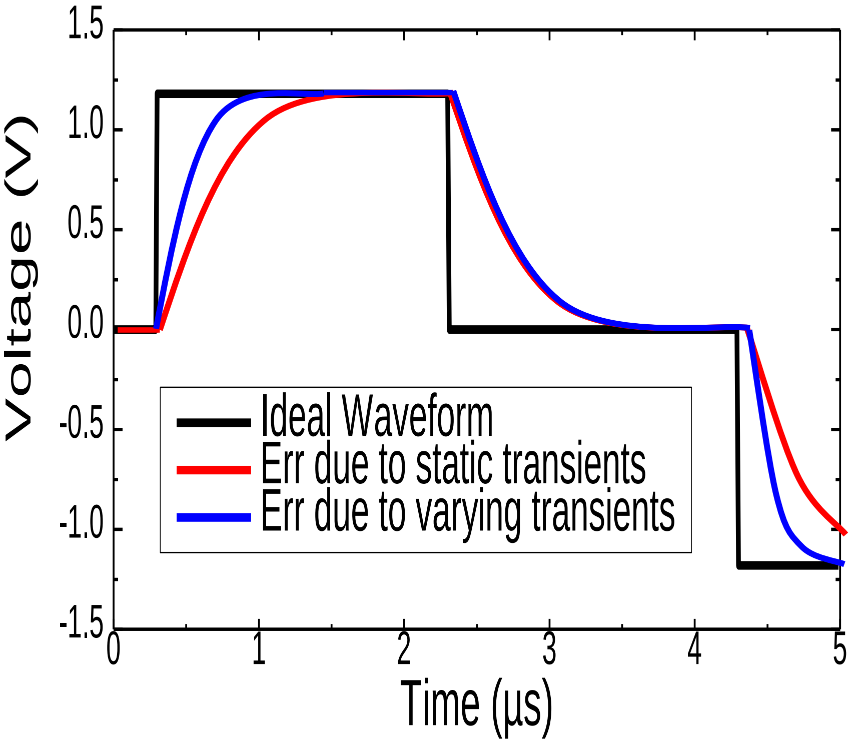
R. Behr et al., *IEEE Trans. Instrum. Meas*. 54, No.2, p. 612, April 2005

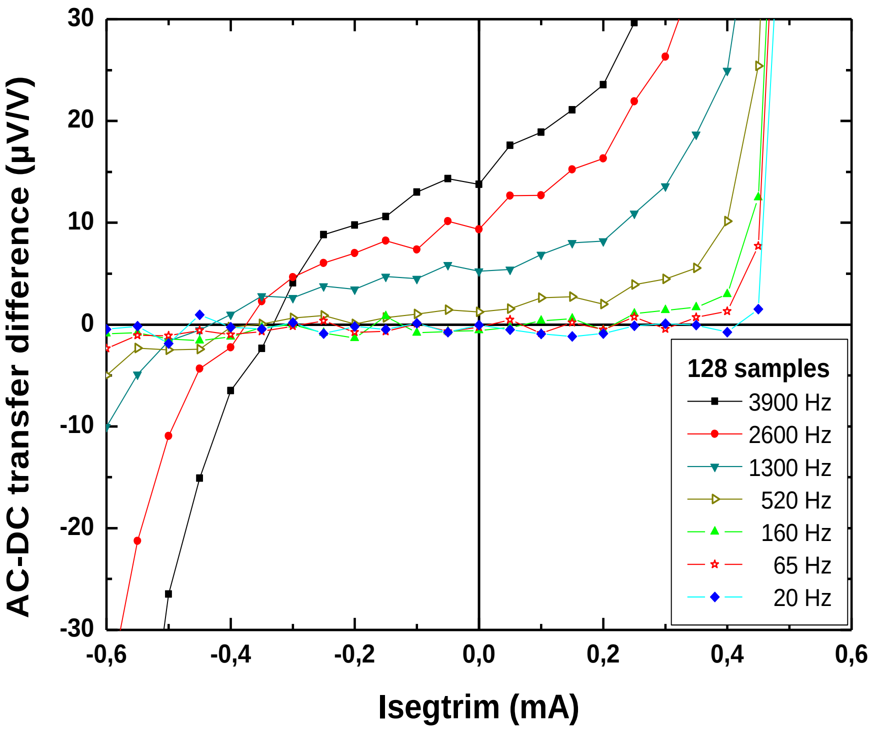
Modelling of the uncertainty contribution



RMS voltage difference between the blue and red line is 10^{-8} for a 1 kHz sine wave with 250 samples!

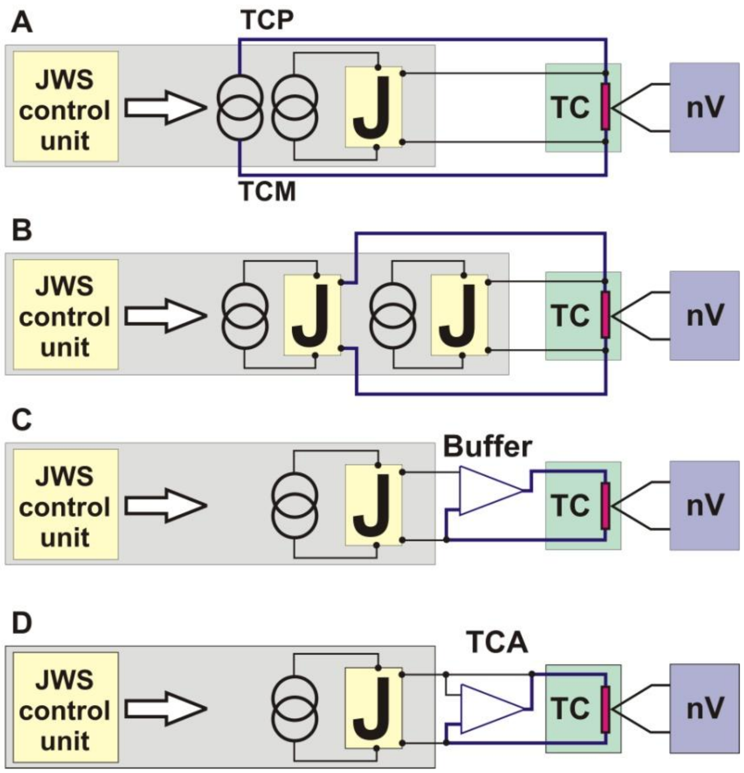
AC synthesis / transients

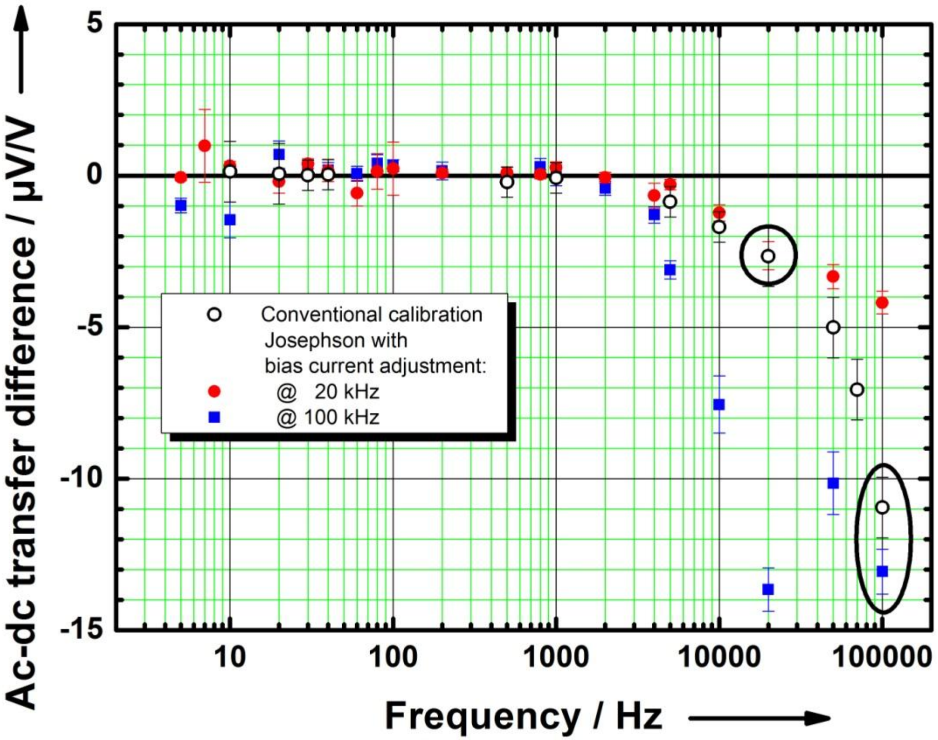




J. Lee et al., IEEE Trans. Instrum. Meas. 58, pp.803, April 2009

TC measurements





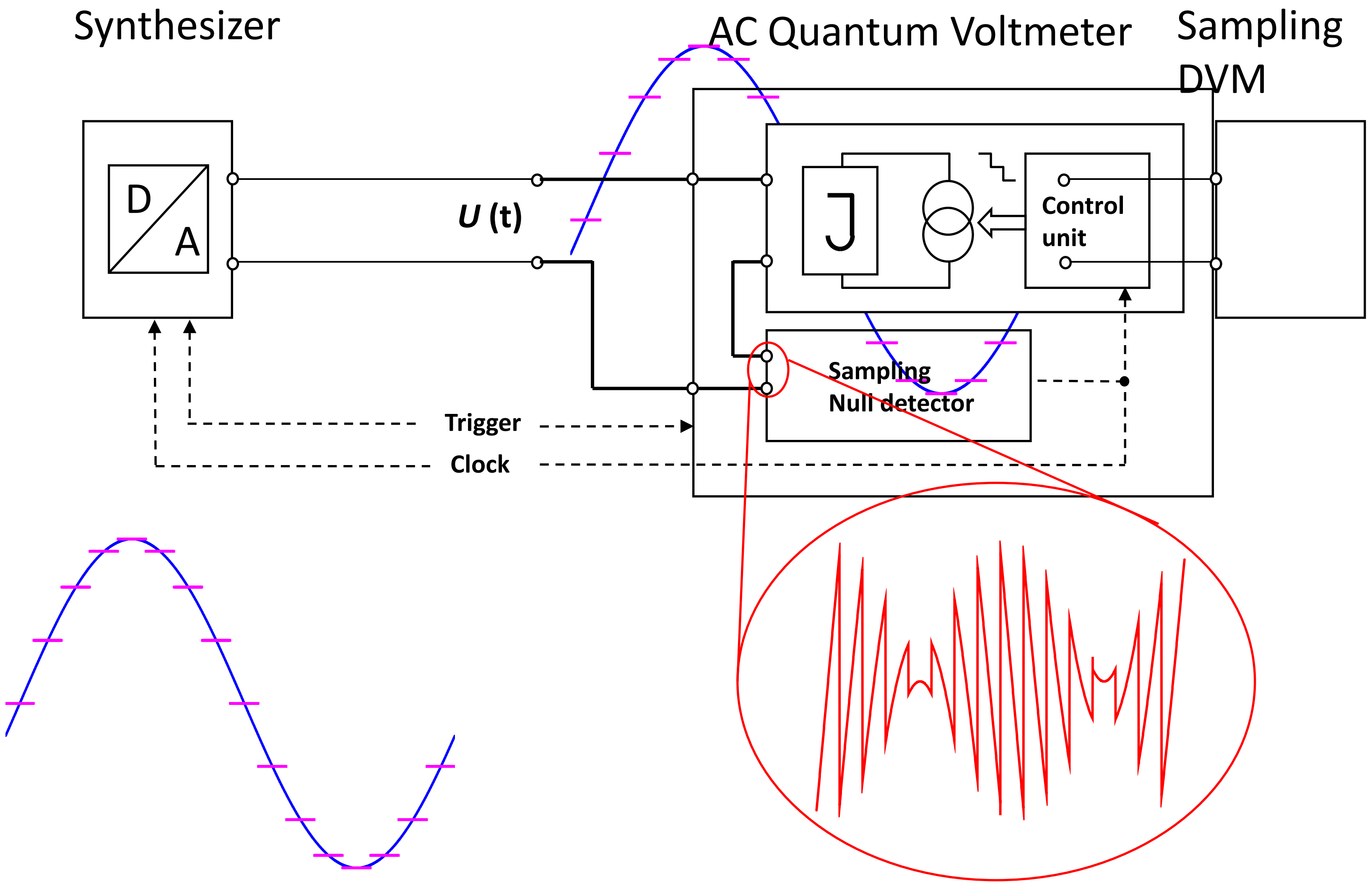
Direct waveform synthesis:

+ **quantum-based – but transients!**
+ different ways to integrate current for TC
+ Uncertainty about 1 µV/V at 1 kHz, better for lower frequencies

PJWS

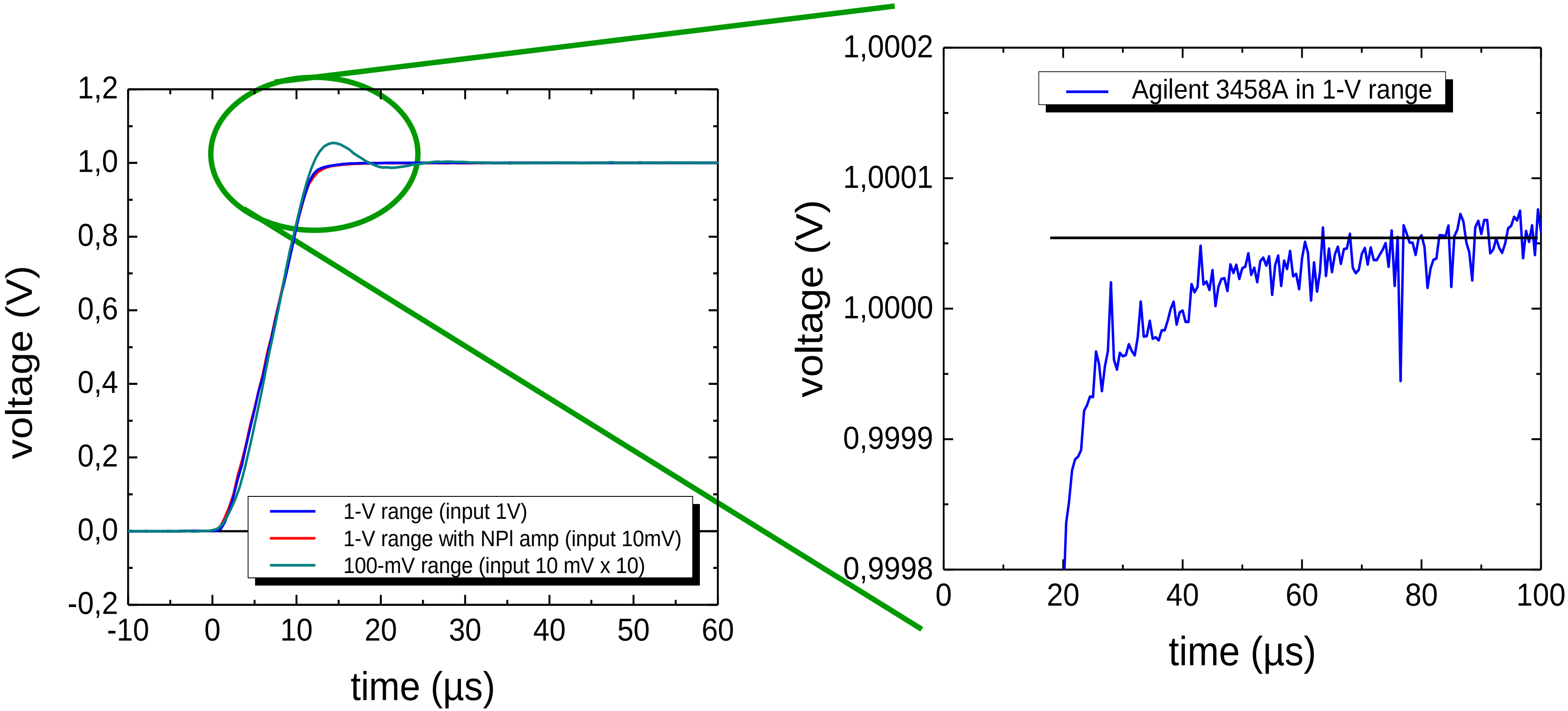

PTB AC-Quantum Voltmeter Smart Panel v2.0
Phase Ctrls Menu
Setup Menus
NI PXI-1036DC
NATIONAL INSTRUMENTS

AC Quantum Voltmeter



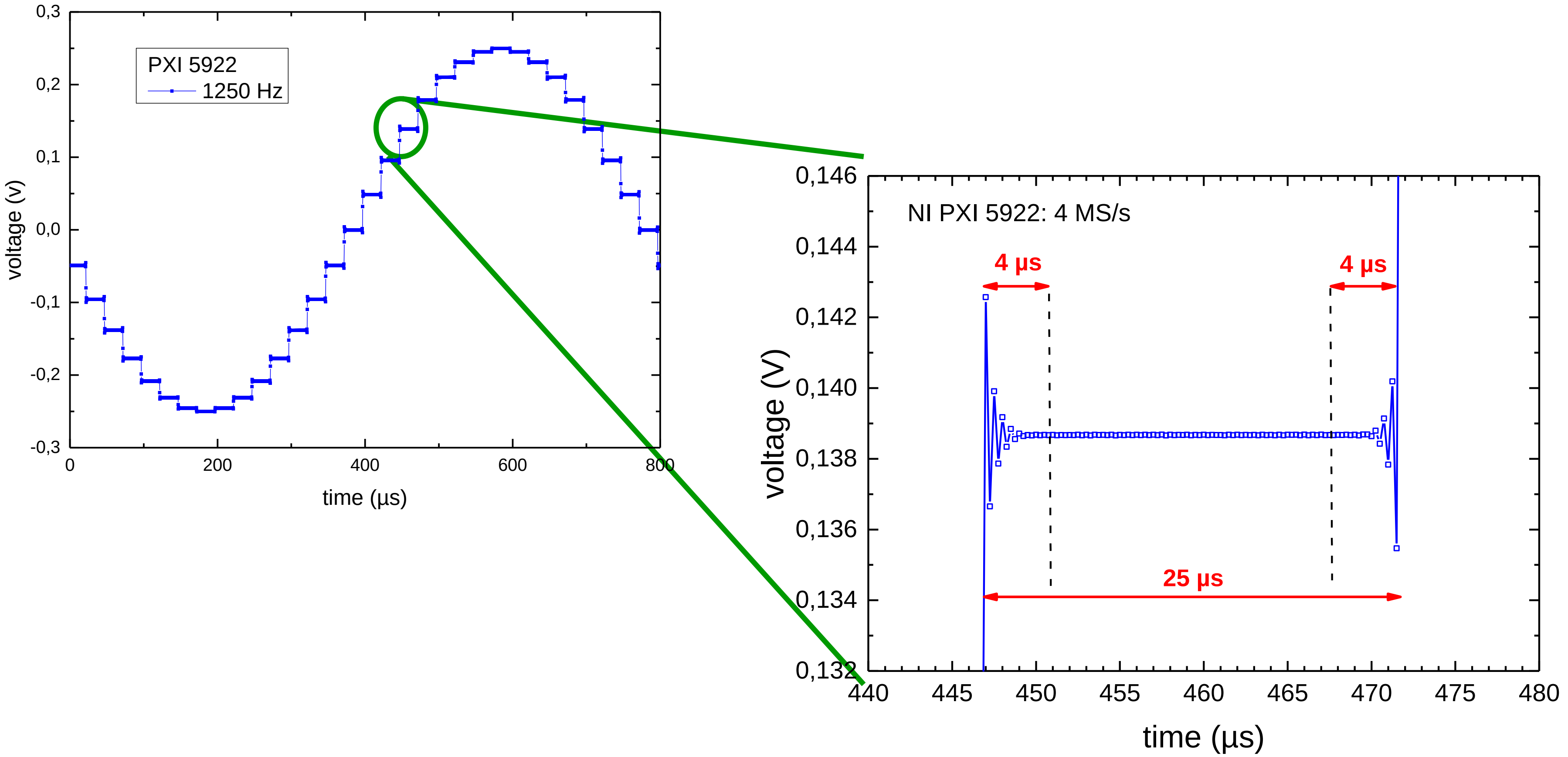
R. Behr et al., *IEEE IM* 56, pp.235-238, April 2007

Transitions: 3458A with 10 µs aperture time



- 100-mV range shows a large ringing due to limited bandwidth
- 1-V range much better to a level of 10^{-4}, then slow time constant of 50-60 µs

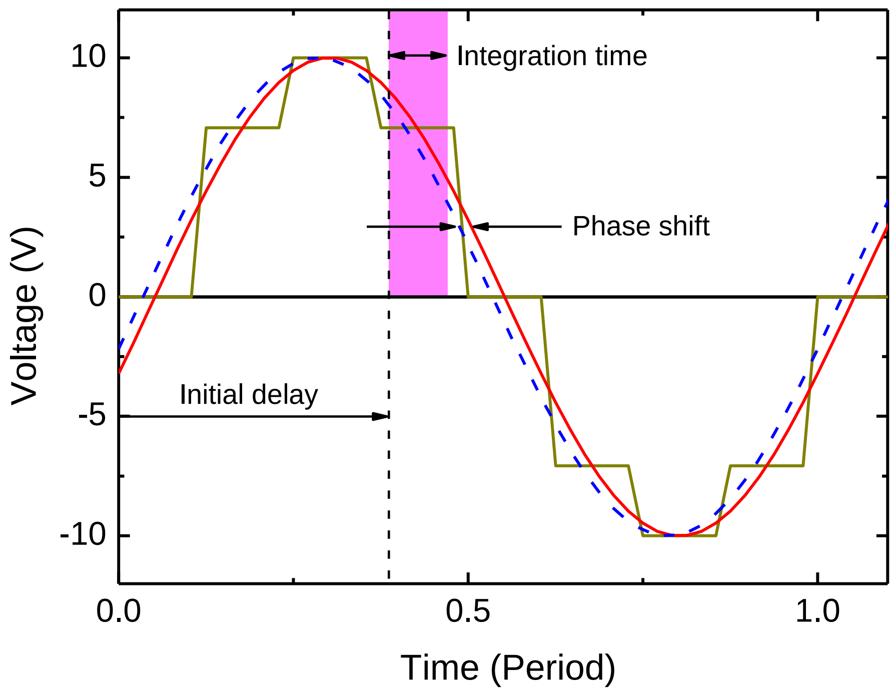
Transitions: ΣΔ-ADC



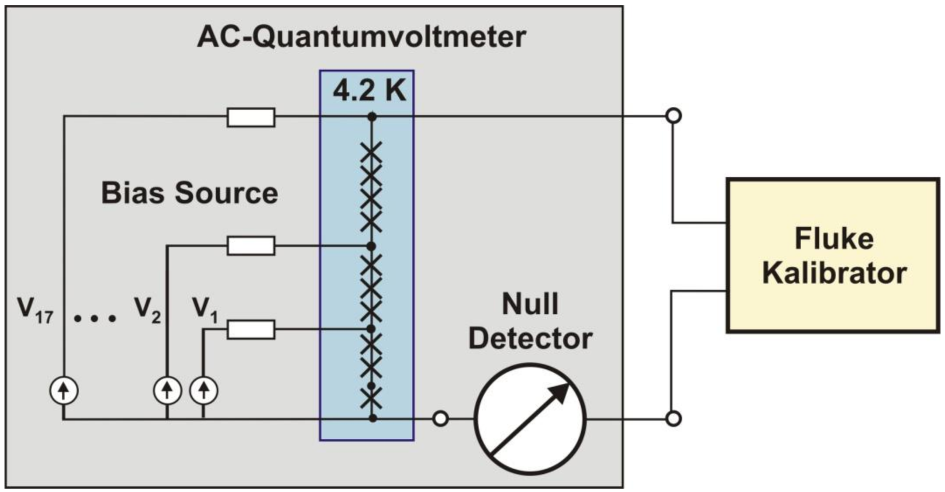
- faster transients are possible

ac-QVM: differential sampling

Parameters

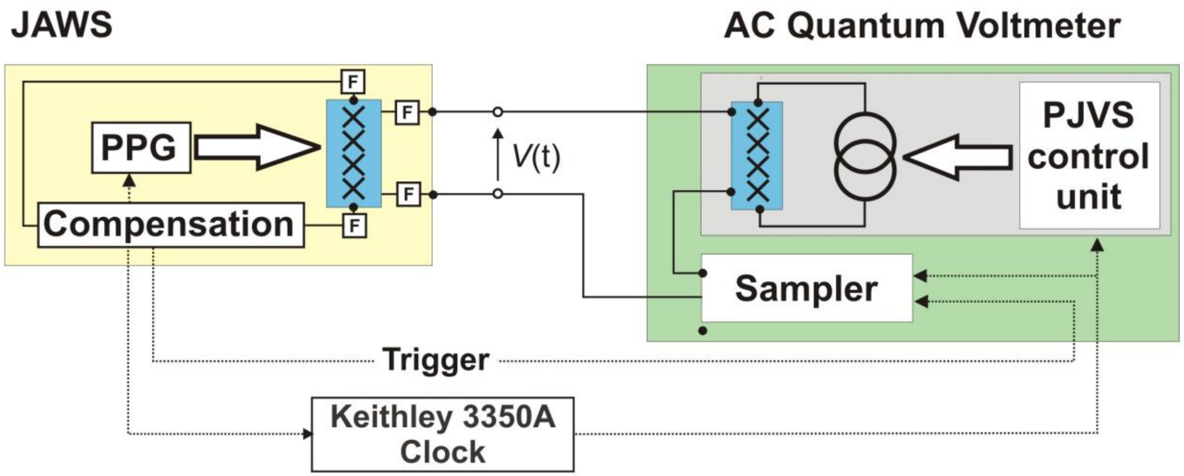


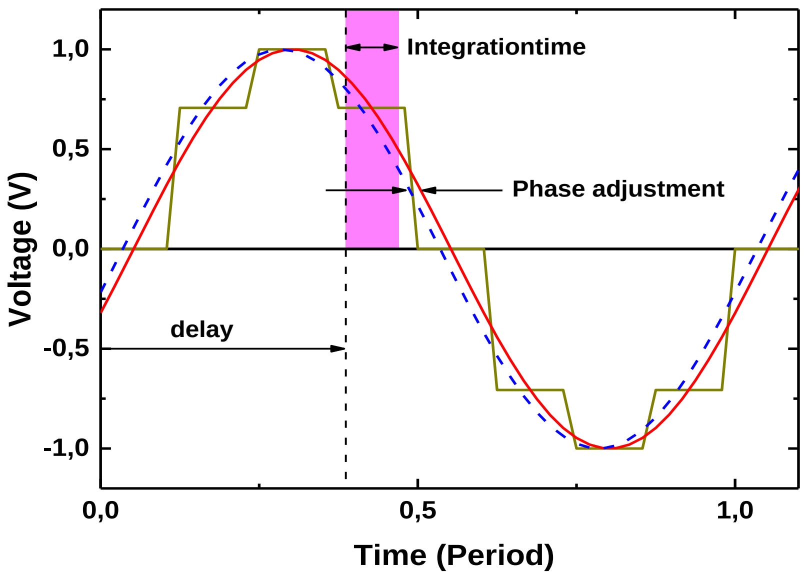
Set-up



- Fluke 5720A
- Proper synchronization
- Fast / precise null detector => NI PXI-5922

Comparison: JAWS versus ac-QVM





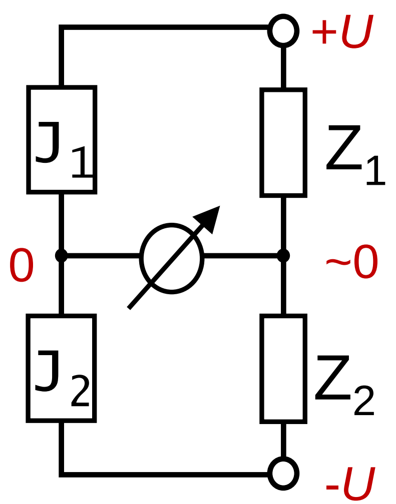
- **ac-QVM tested for measurements at 10^8 level**

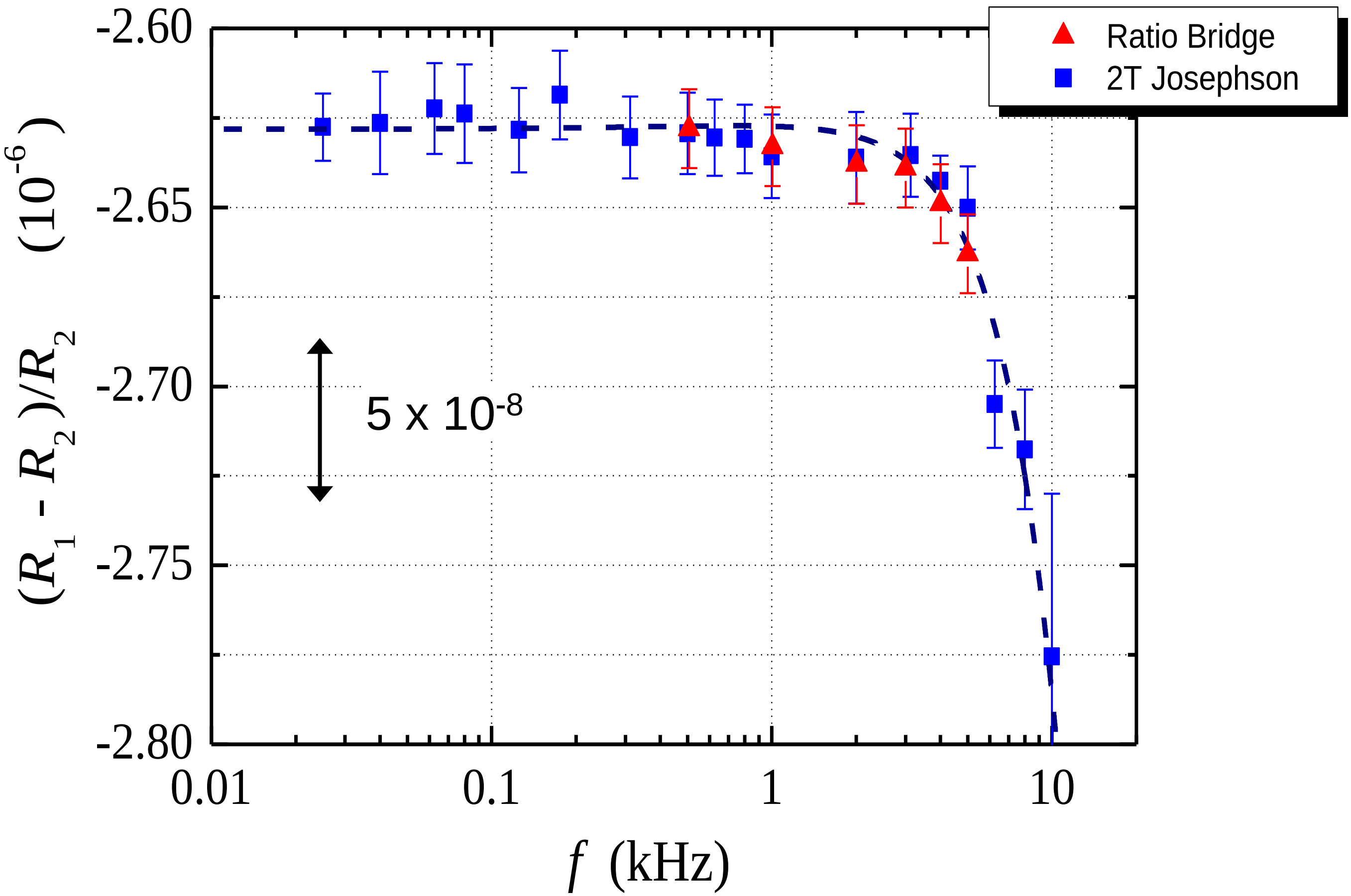
Jinni Lee, CPEM 2014

R. Behr et al., Metrologia 2015

Josephson bridges for Impedance measurements

+ **quantum-based**
+ **free amplitude + phase setting**
+ **automated**
+ **DC to 10 kHz**





Acknowledgement

Thank you !

This work was partly carried out with funding by the European Union within the EMRP JRP SIB59 Q-WAVE.
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Josephson Arbitrary Waveform Synthesizer

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outline

1. motivation and principle
2. circuit design
3. fabrication
4. setup
5. waveforms
6. precision
7. applications
8. summary

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Motivation

Increasing demand for high-precision AC voltages

(basis : Josephson effect)

↓

- **AC voltage sources with quantum-accuracy**
- **synthesis of arbitrary waveforms**
- **precise audio-, HF- and noise-references**
- **large frequency-bandwidth : DC….MHz**

PJVS and JAWS : basic principle

AC-Programmable Josephson Voltage Standard

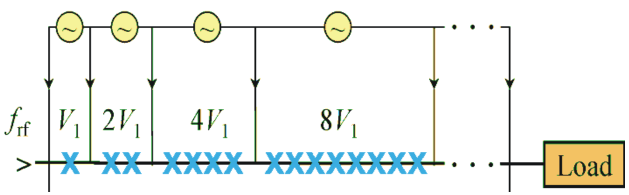
Josephson Arbitrary Waveform Synthesizer

70 GHz

$$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f$$

15 GHz

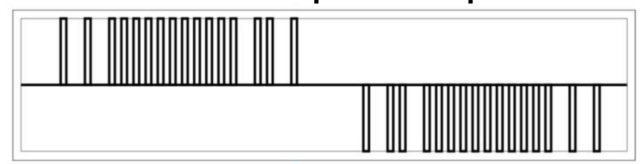
binary



$M(t)$

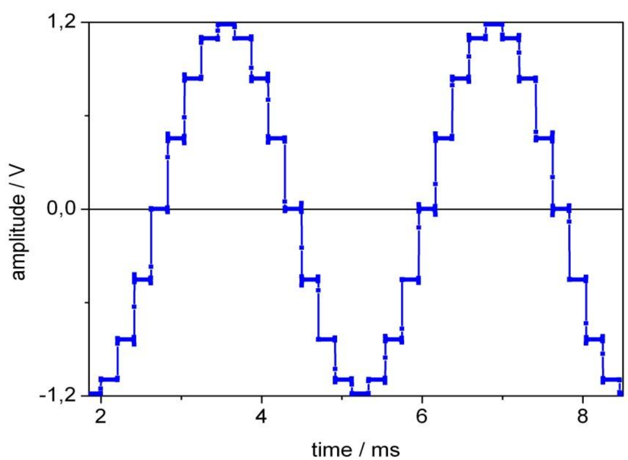
$f_p(t)$

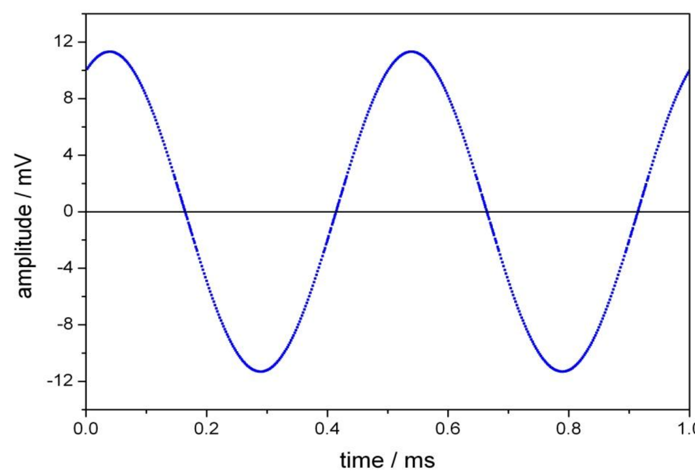
pulse operation



number Josephson junctions

pulse repetition frequency





Principle of pulse-mode operation

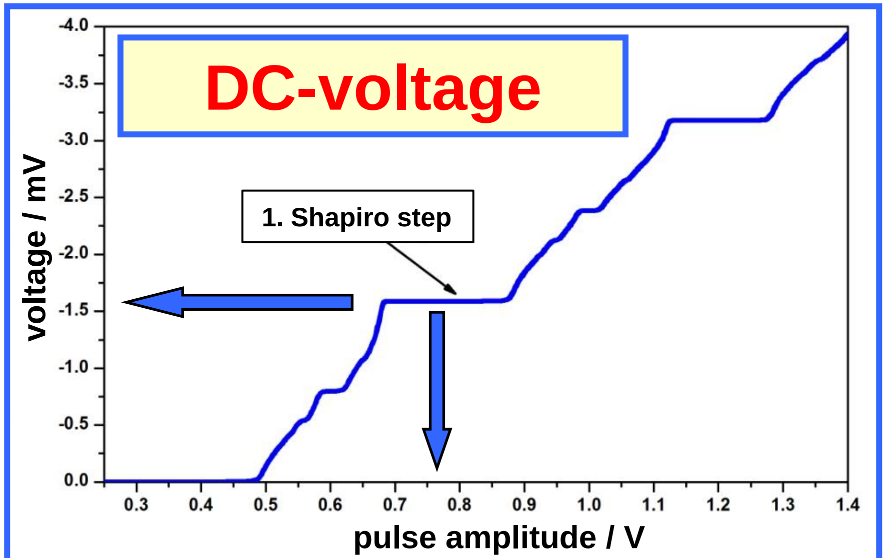
idea : R. Monaco, *J. Appl. Phys.* 68 (1990) 679
first realization @ NIST : S.P. Benz and C.A. Hamilton, *Appl. Phys. Lett.* 68 (1996) 3171

a current pulse (pulse repetition frequency f_p) transfers N flux-quanta $\Phi_0 = h/2e$ through a Josephson junction (number of junctions M).

pulse repet. freq. $f_p = const.$

Josephson-equation :

$$V_{DC} = M \cdot N \cdot \Phi_0 \cdot f_p$$



pulse repet. freq. $f_p \neq const.$

Josephson-equation in pulse-mode :

$$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f_p(t)$$

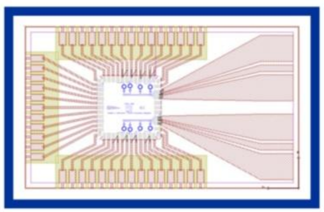
AC-voltage arbitrary waveform

JAWS : practical realization

computer

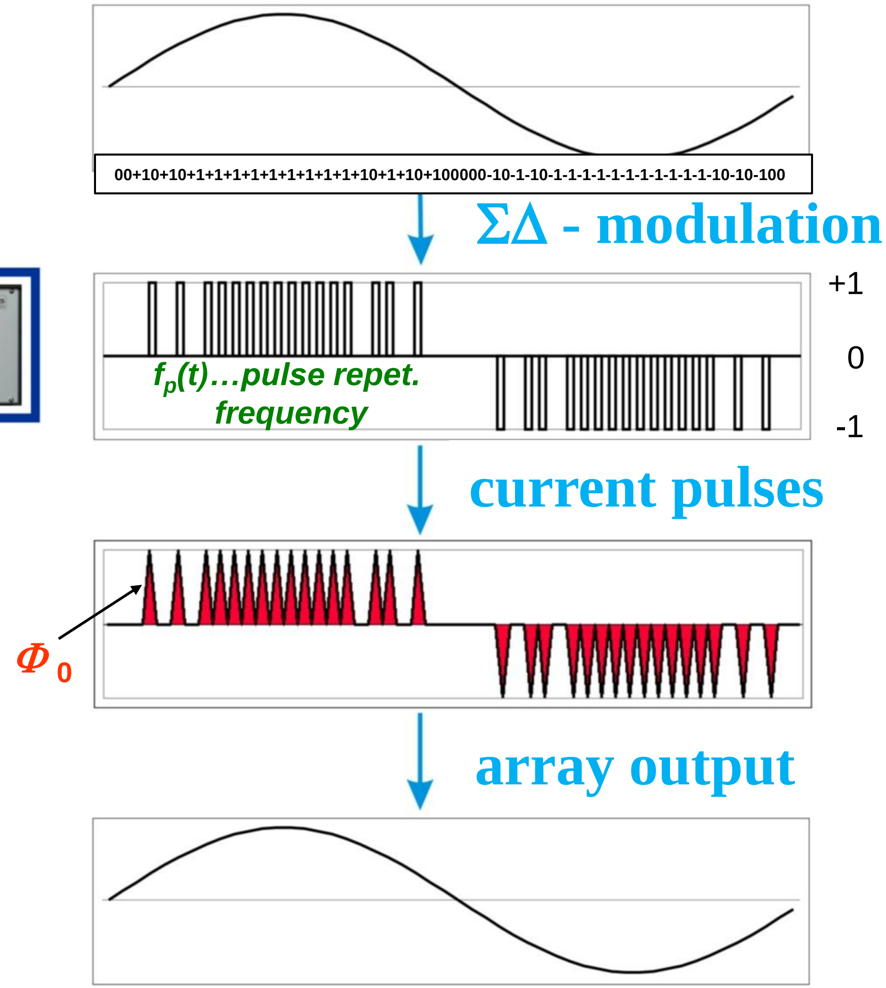
pulse-pattern-generator (PPG)

SNS **JAWS** chip @ LHe : 4.2 K



spectrum analyzer

arbitrary waveform



quantized waveform

$$V(t) = M \cdot N \cdot \Phi_0 \cdot f_p(t)$$

Increasing output voltage towards 1V

Josephson-equation in pulse-mode :

$$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f_p(t)$$

status quo @ PTB :

- **maximum clock frequency (= maximum f_p): f_{clock} = 15 GHz**
- **maximum 2 x arrays @ 1 chip**

Target 1 V - increase the number *M* of "active" junctions :

- **more junctions per array : triple-stacked junctions : technology**
- **up to 8 x arrays in series (@ 4 chips) : experimental setup**

$V_{RMS} \approx$ 1000 mV : about 60 000 junctions ($A_{\Sigma\Delta} \approx 0.80$)

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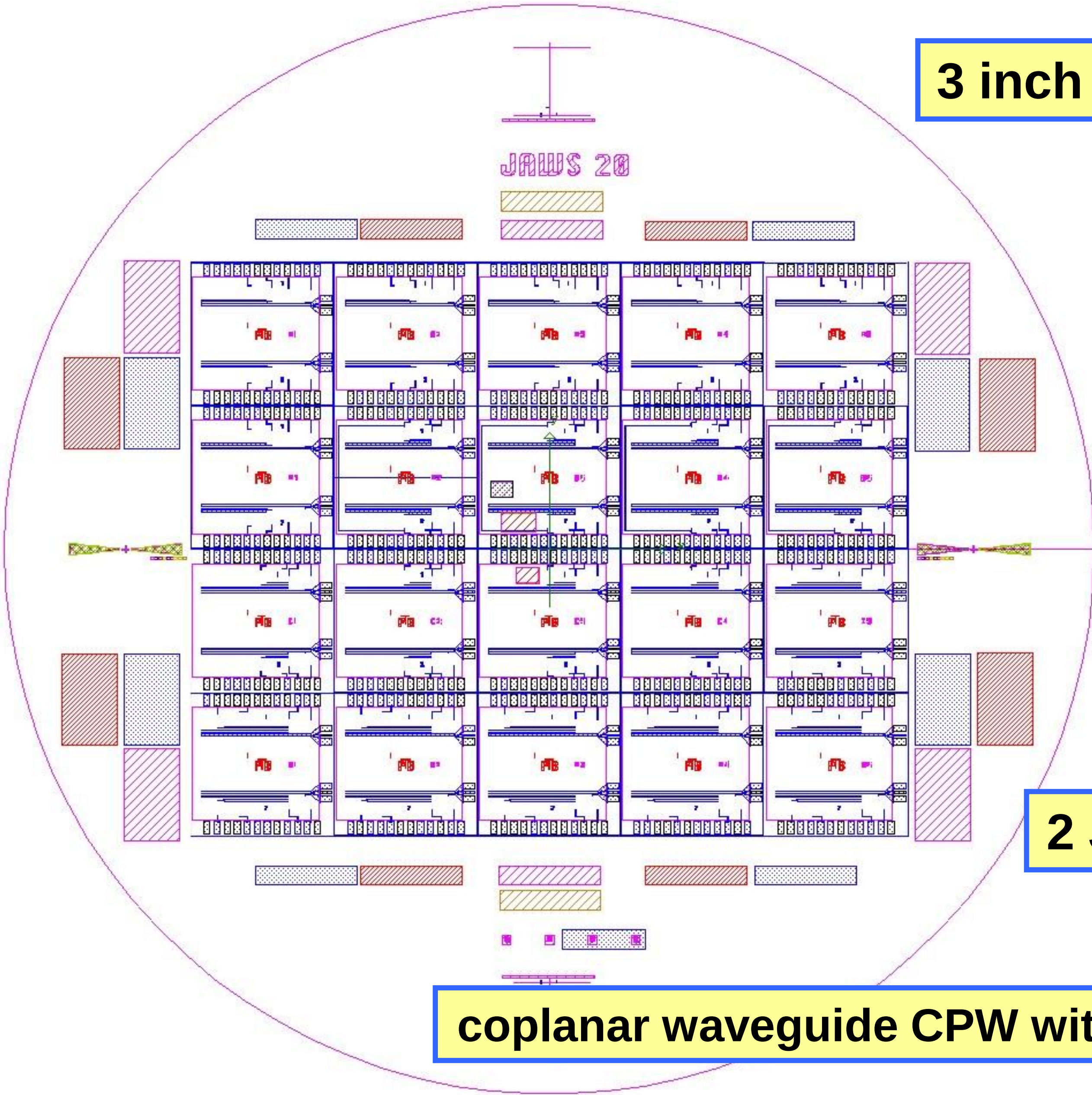
Design : example wafer - layout



3 inch Si - wafer

20 chips

@ wafer

chip-size :

10 mm x 10 mm

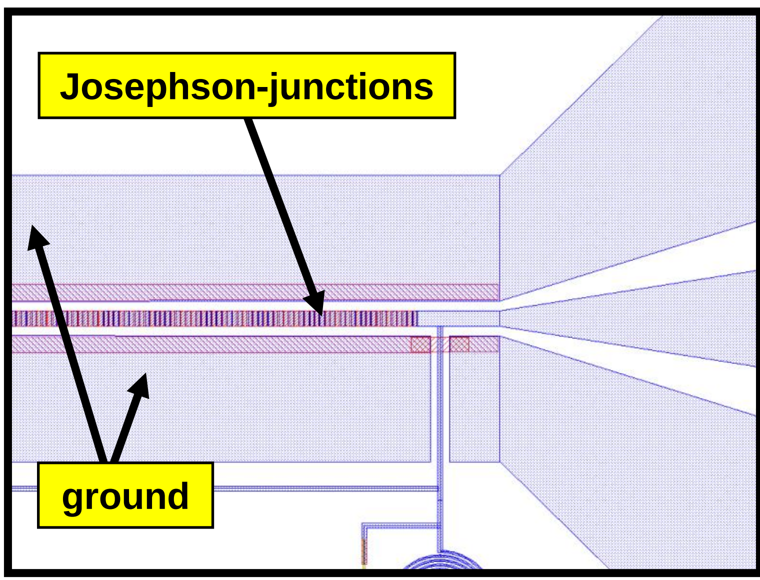
2 JAWS arrays @ chip

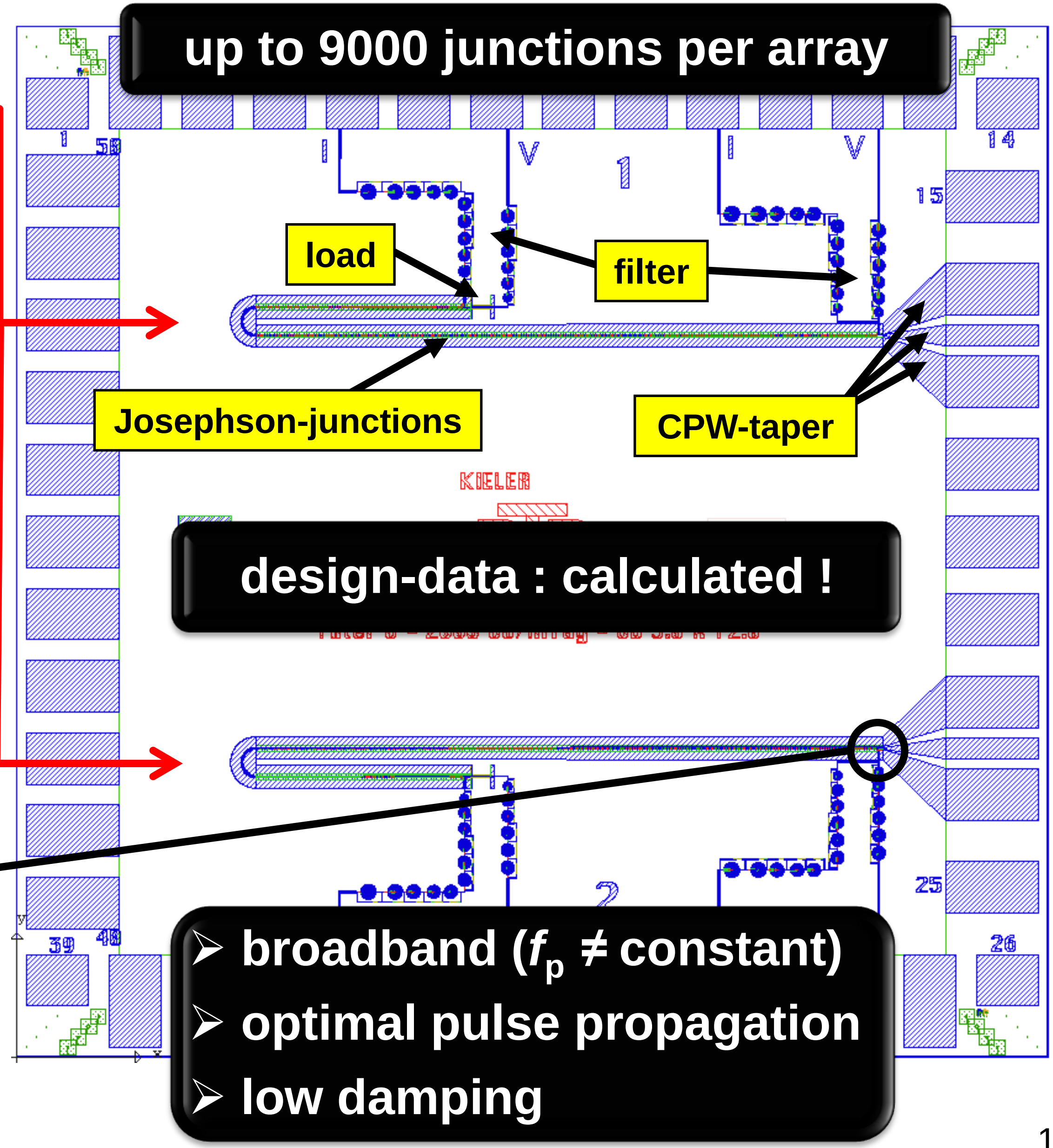
coplanar waveguide CPW with on-chip LCR-filter

Design : SNS series arrays

2 arrays @ chip :

- coplanar waveguide (CPW)
- CPW : 50 Ohm-taper
- Load : 50 Ohm
- SNS-type junctions
- on-chip LCR-filter





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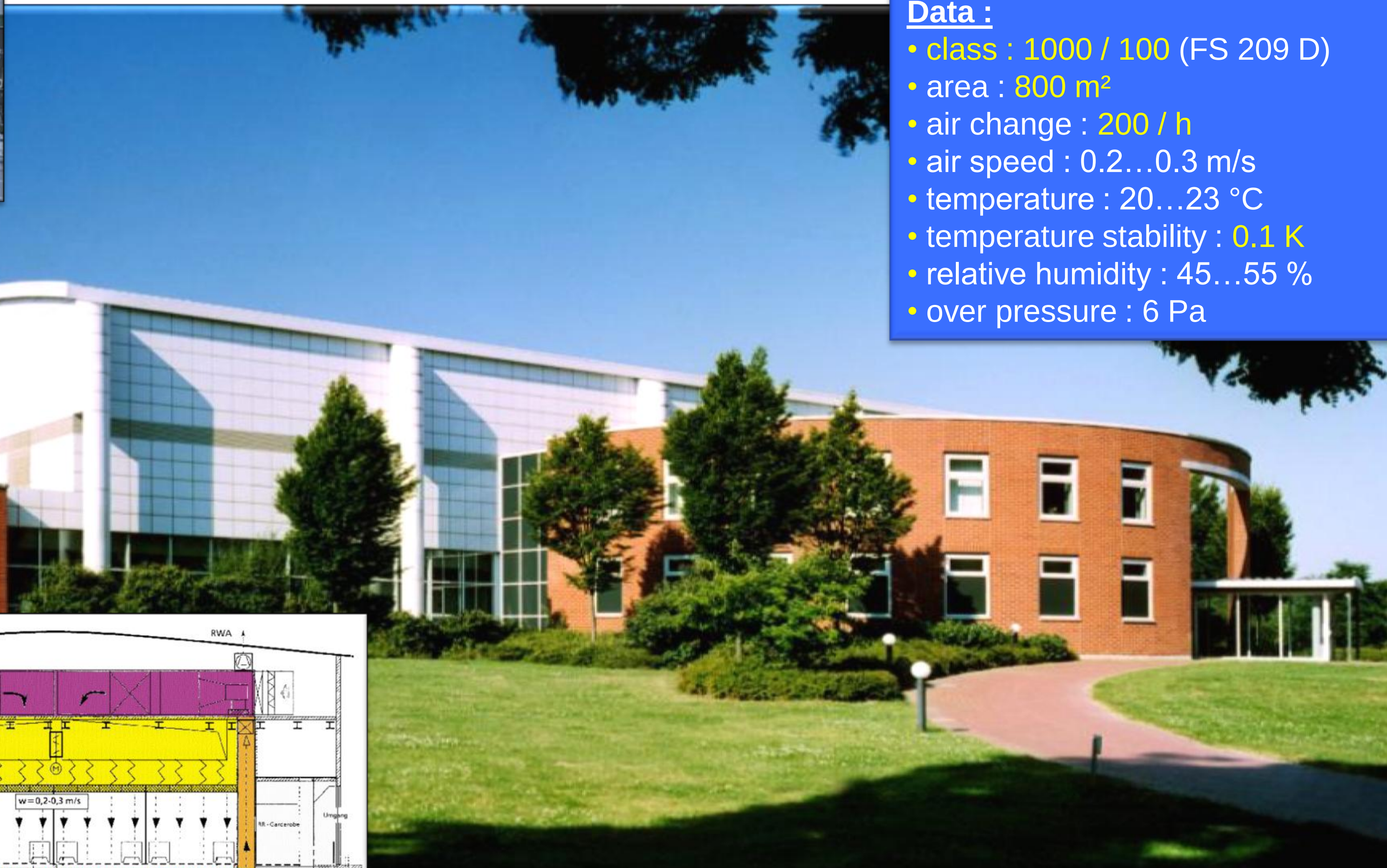
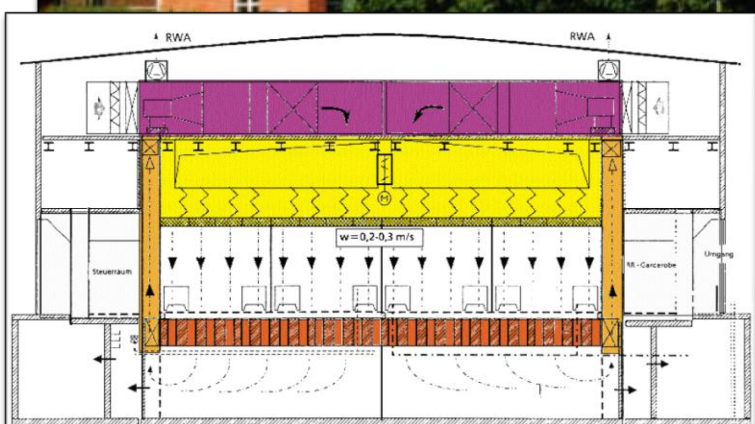
PTB clean room : classification

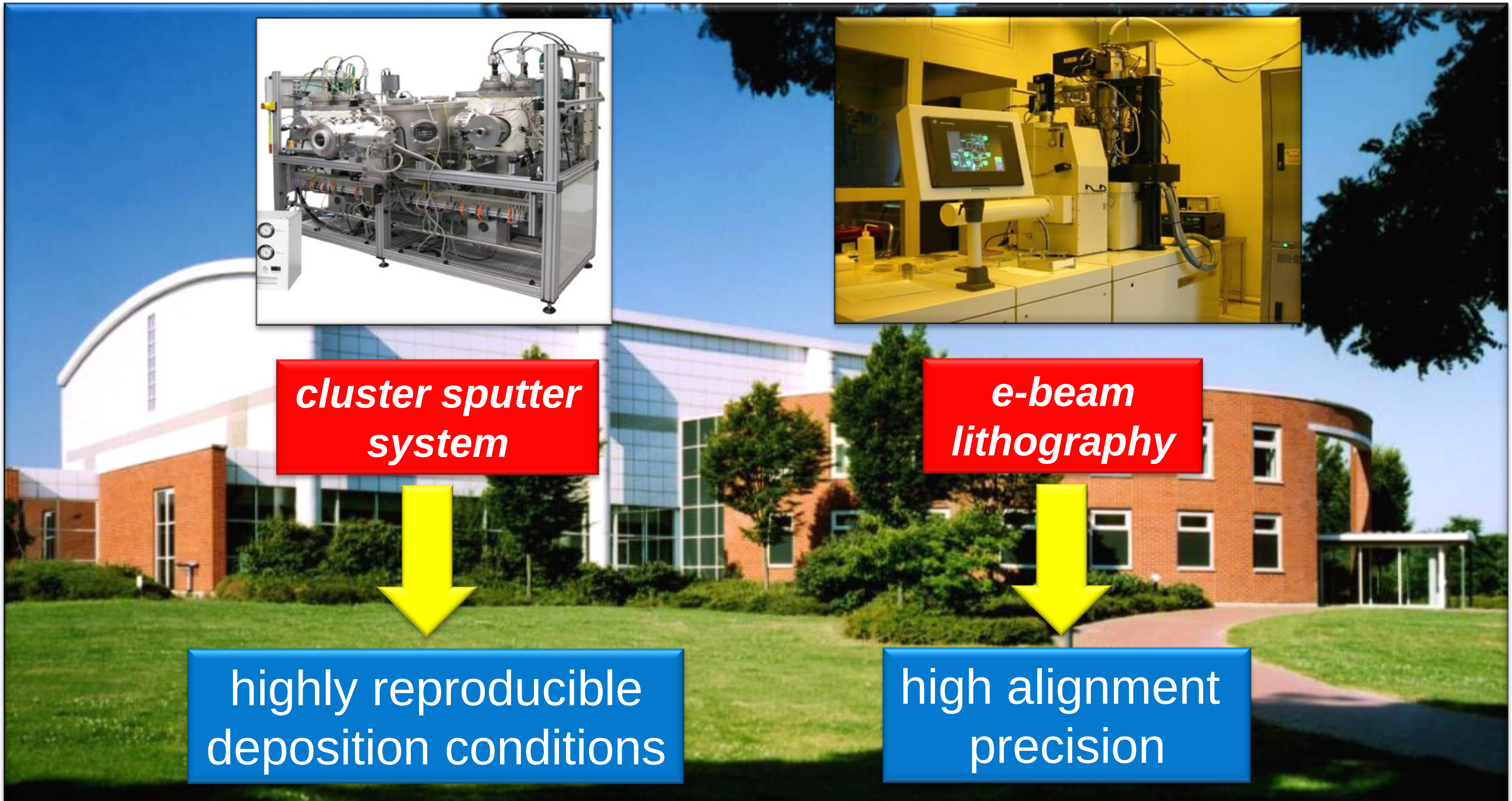


Data :

- class : 1000 / 100 (FS 209 D)
- area : 800 m²
- air change : 200 / h
- air speed : 0.2…0.3 m/s
- temperature : 20…23 °C
- temperature stability : 0.1 K
- relative humidity : 45…55 %
- over pressure : 6 Pa



JAWS: major fabrication tools



UNIVEX 450C – Cluster - Sputter - System

Nb_xSi_{1-x} parameter for **70 GHz and 15 GHz**

6 chambers

fully automatic

Nb, Si, AuPd, HfTi, Al, Al_2O_3

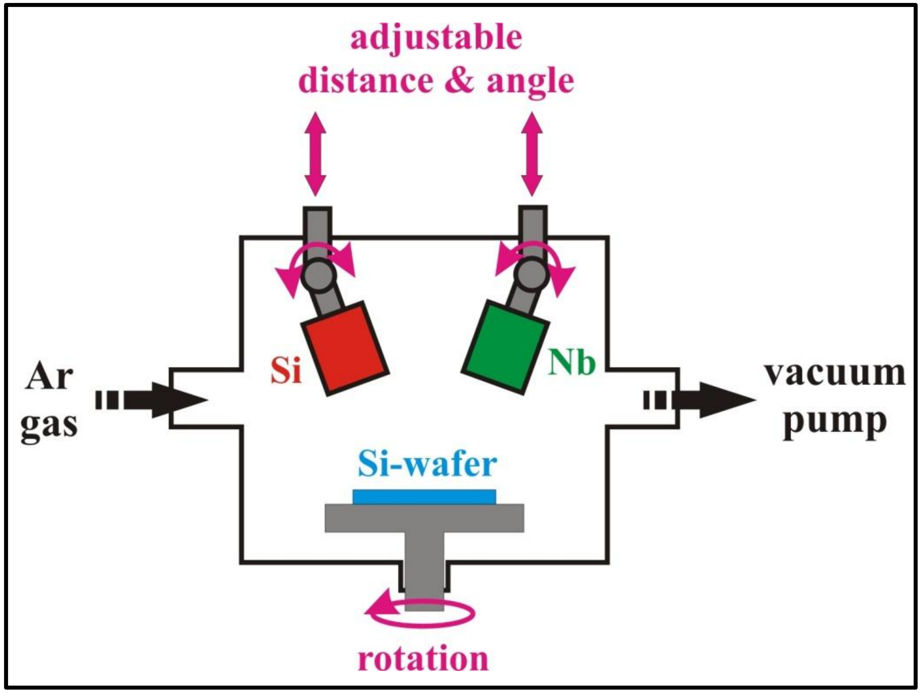
SNS / SIS / SINIS

2 parameter to optimize :

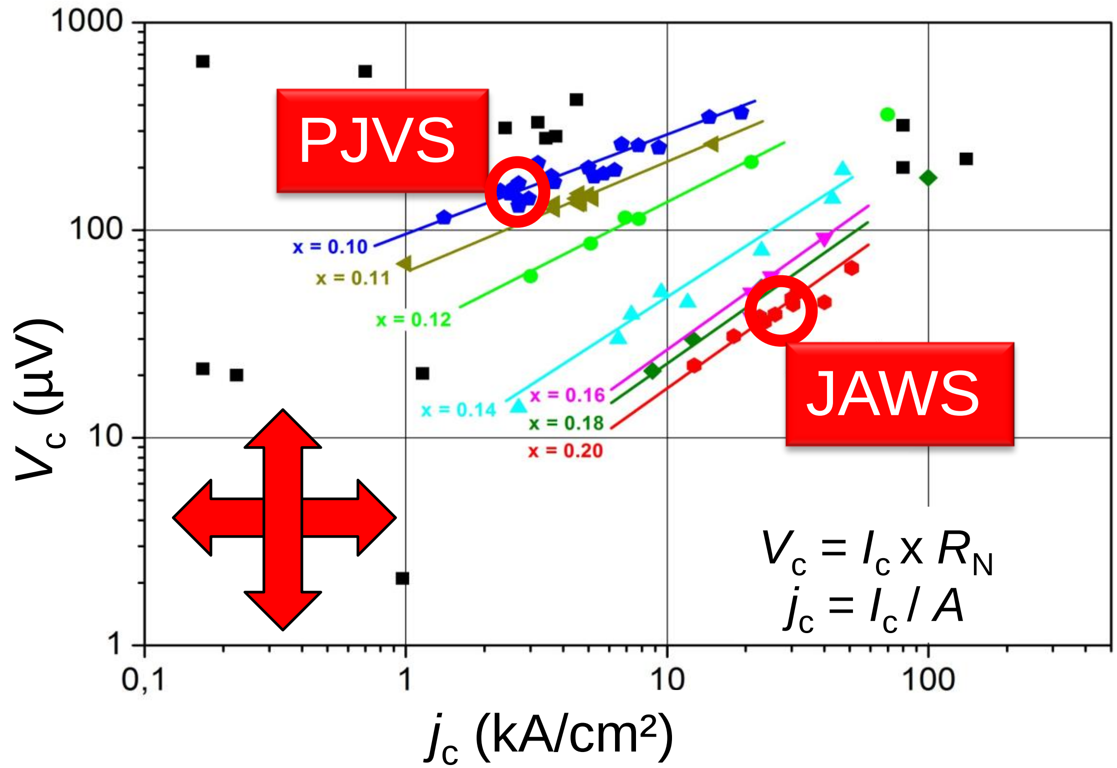
JAWS : x ≈ 20%, d_{NbSi} ≈ 30 nm @ 15 GHz

SNS junctions : Nb_xSi_{1-x}

Nb_xSi_{1-x} : co-sputter !

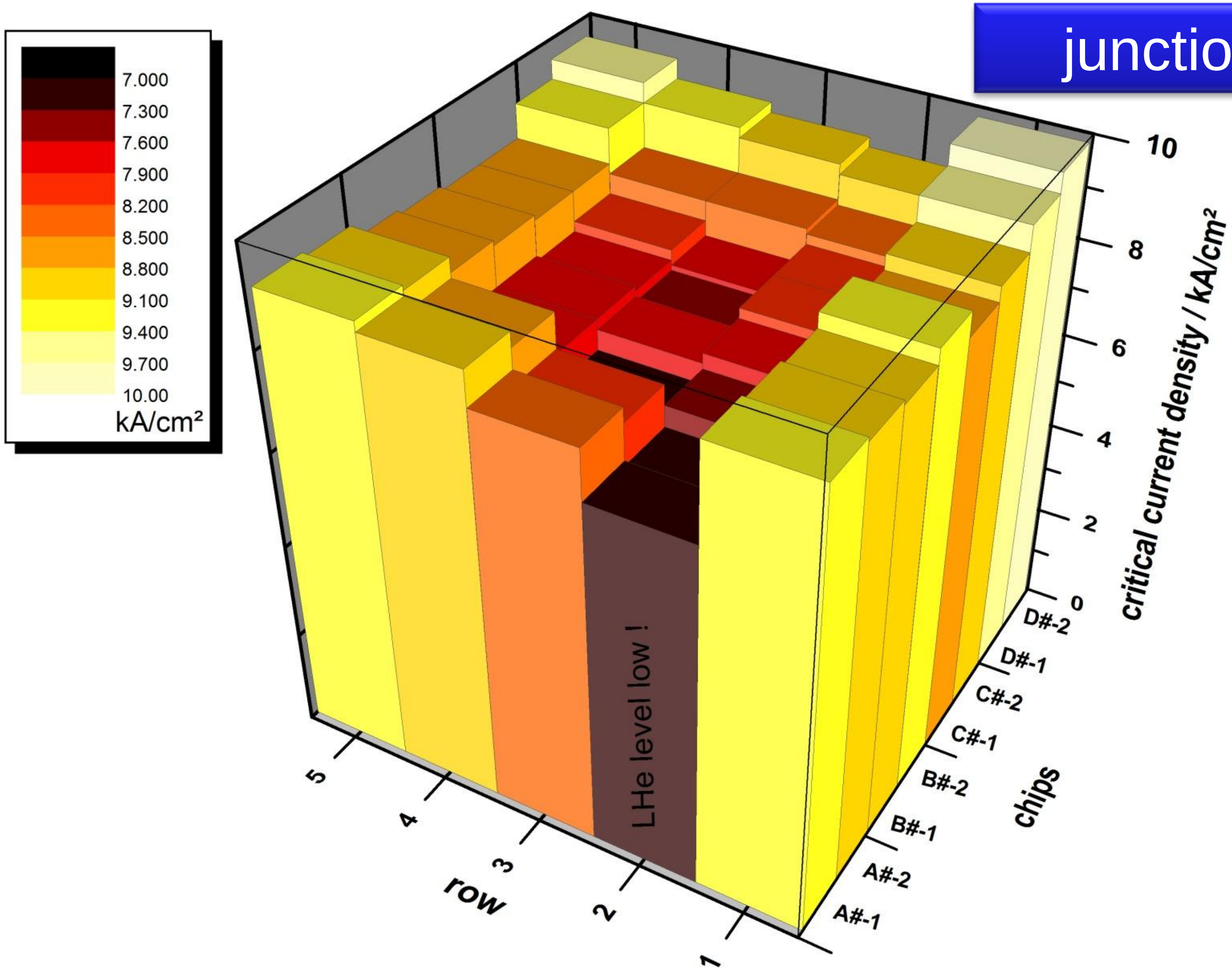


thickness *d* und Nb-content *x*



parameter adjustable in a
wide range nearly **independendly** !

UNIVEX : before source optimization



junctions : double stacked

all 40 circuits measured

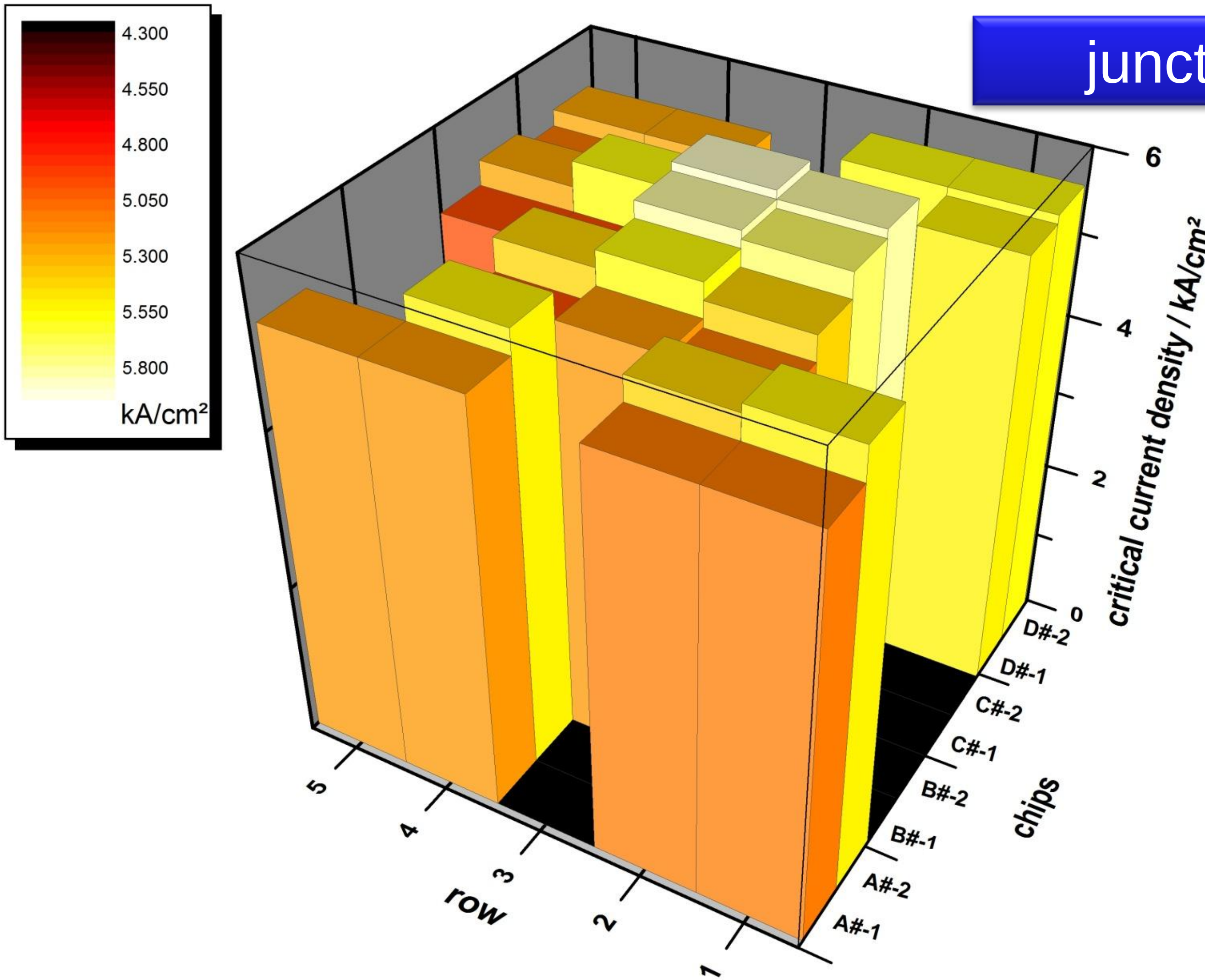
200 000 junctions : 4 defect only

junction - yield : 99.998 %

current density distribution @ wafer-surface :

deviation from mean value : 7.3 %

UNIVEX : after source optimization



junctions : triple stacked

30 circuits measured (from 40)

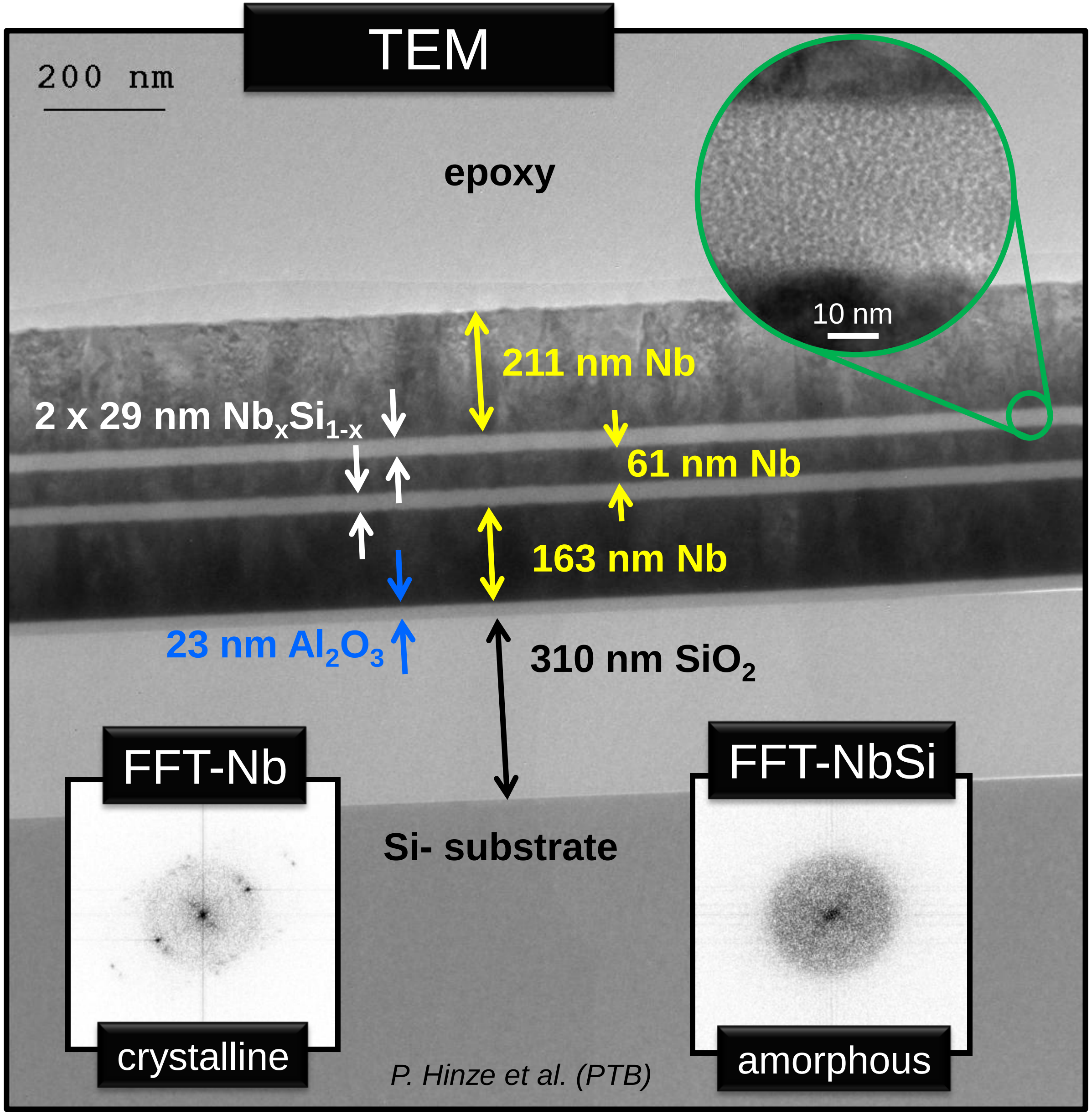
228 000 junctions : 9 defect only

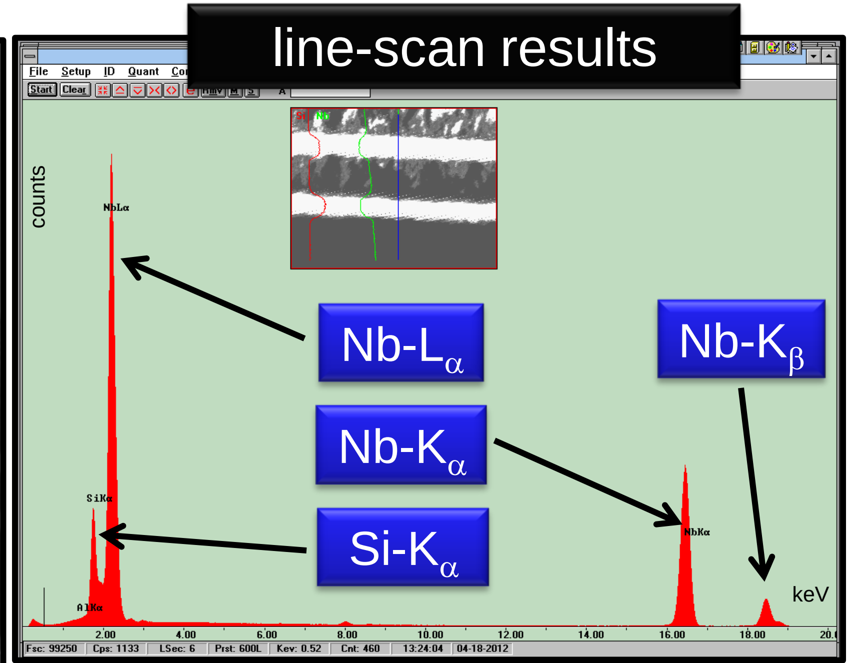
junction - yield : 99.996 %

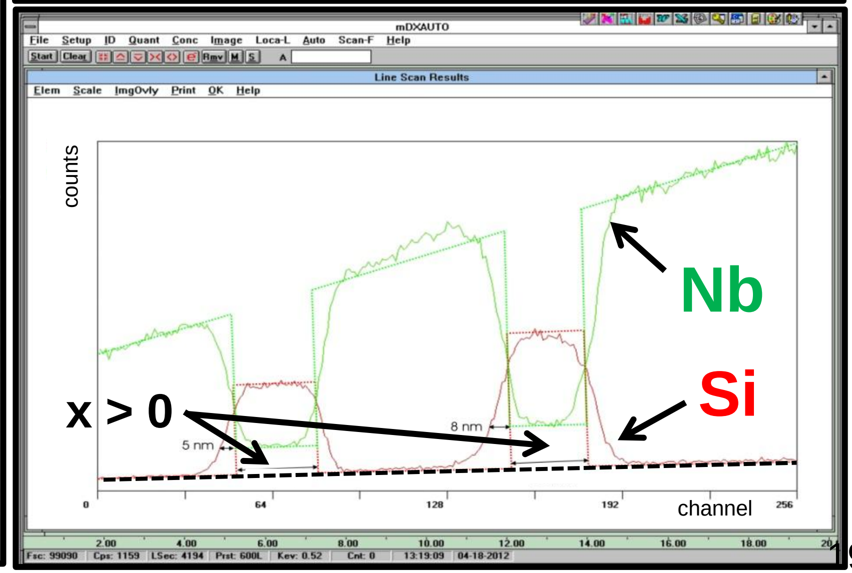
current density distribution @ wafer-surface :

deviation from mean value : 4.6 %

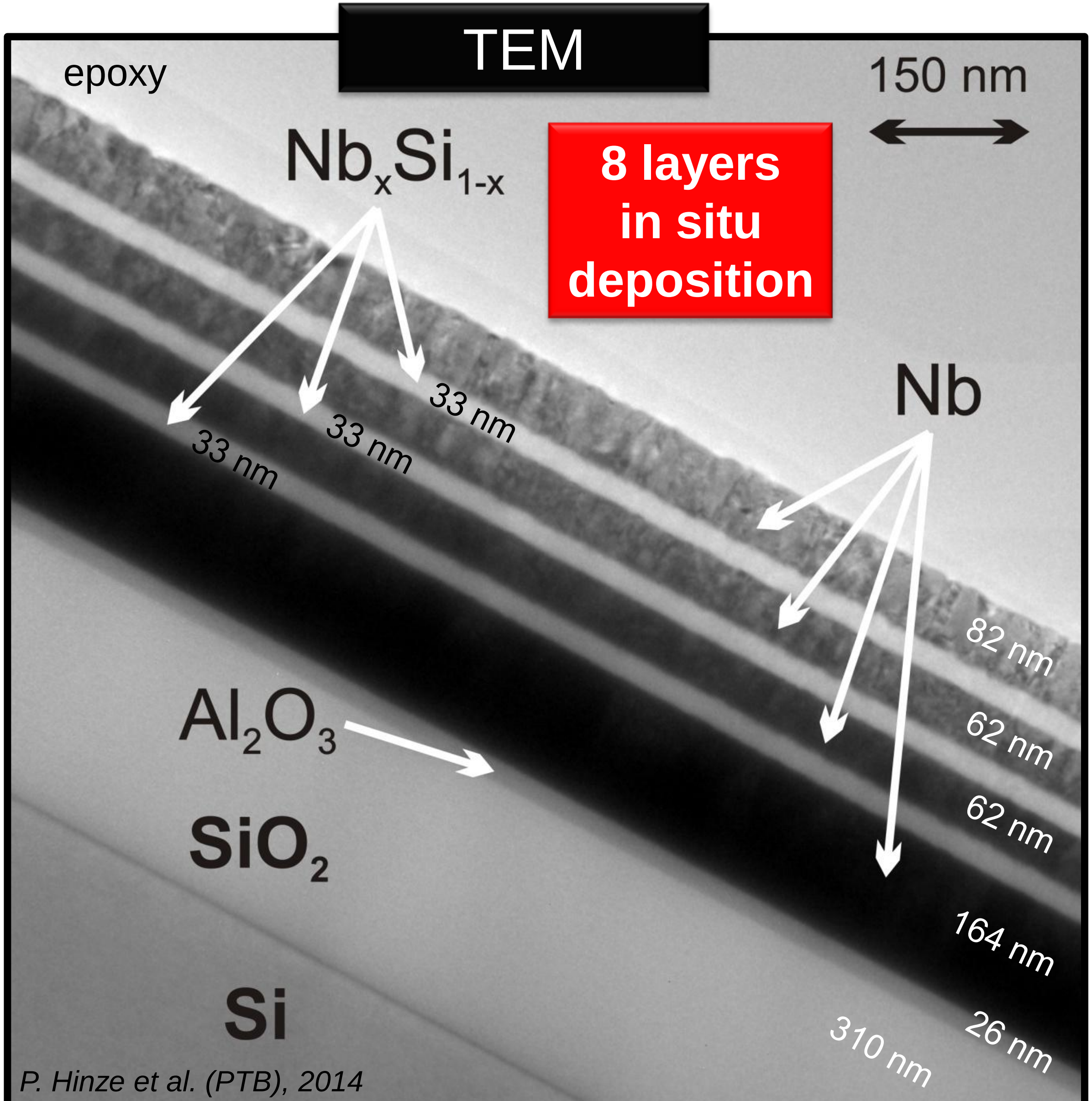
SNSNS double-stacked junctions







SNSNSNS : triple-stacked junctions



UNIVEX 450C - system

homogeneous & reproducible deposition conditions

3 x junction number

3 x output voltage (for a given design)

window-process (I) : fabrication tools

deposition :

- UNIVEX : Al_2O_3 , Nb, Nb_xSi_{1-x}, AuPd
- PECVD : SiO_2

lithography :

- ebeam system : array structures
- optical mask aligner : contact pads
- spinner, hotplates : ebeam- / photo-resists

pattering :

- ICP RIE : Nb, Nb_xSi_{1-x}, SiO_2
- HF-solution : SiO_2 (pads)

diagnosis :

- reflection spectroscopy : layer thickness
- contact profilometer : layer thickness
- prober system : resistance
- light microscopes : defects
- SEM : JJ-size, edge quality
- TEM : layer structure

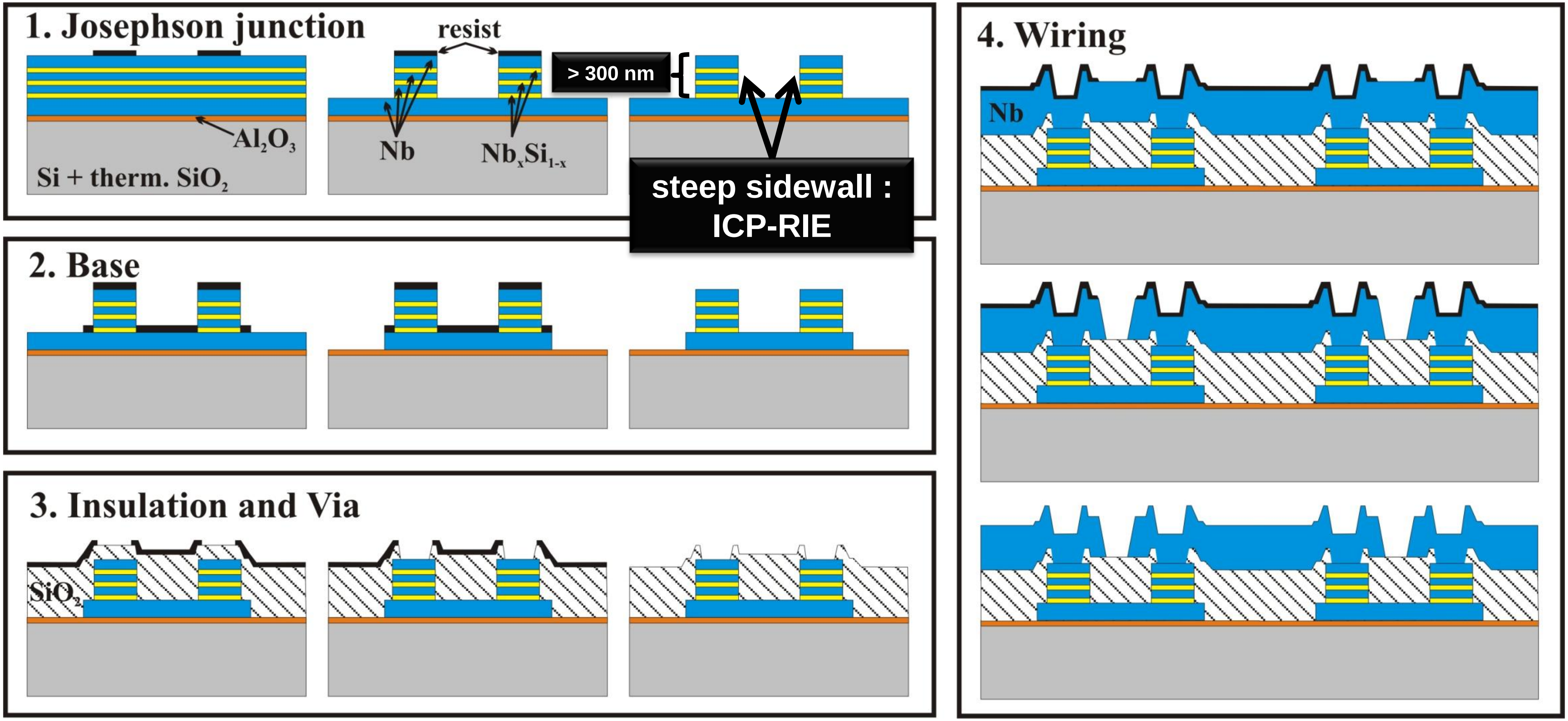
other :

- wafer cleaning systems
- wafer dicing systems
- chip bonding systems

clean-room building is one of the major facilities of PTB

hosted by department 2.4 : quantum electronics

window-process (II) : fabrication steps



5. Load : AuPd resistors by lift-off

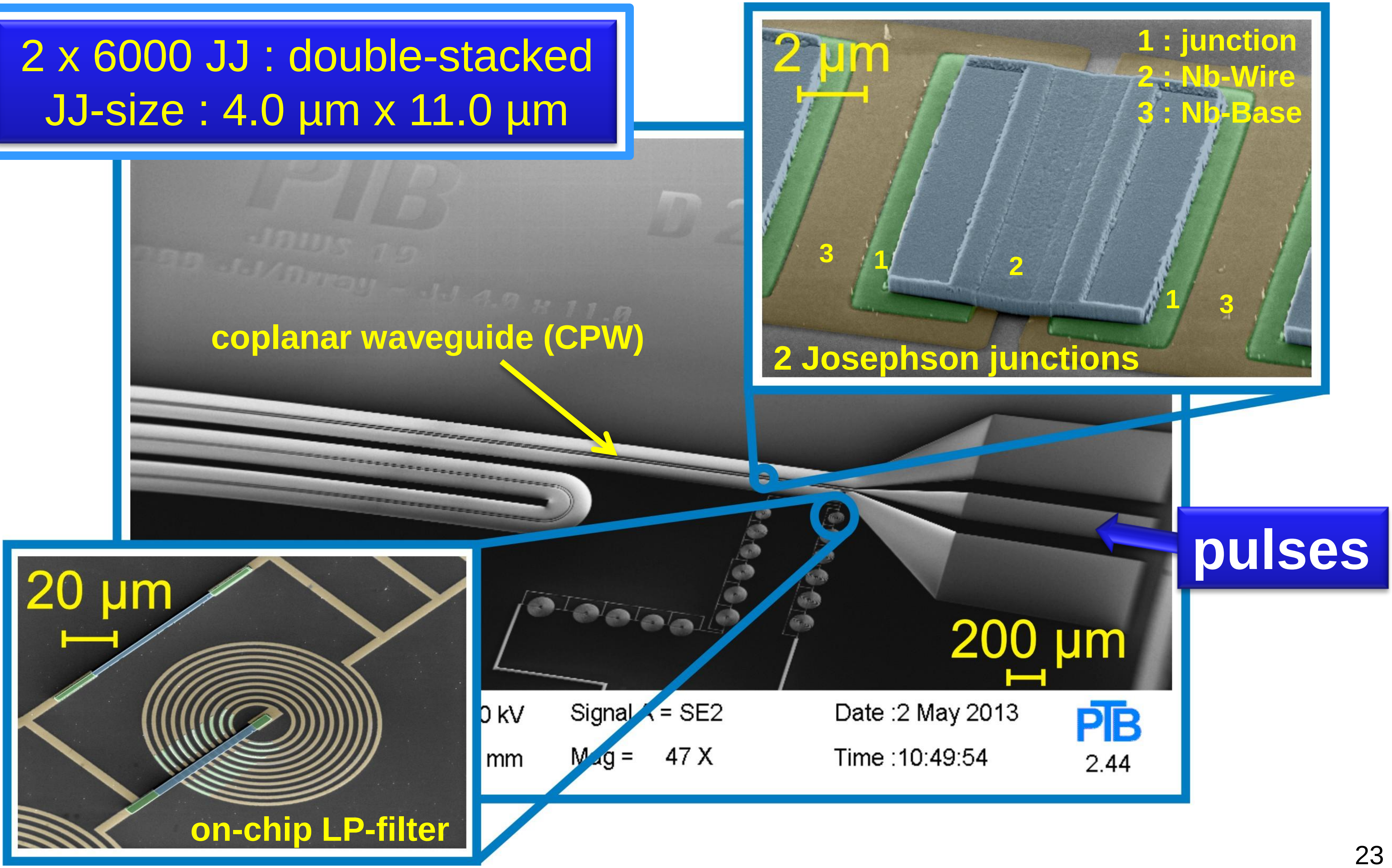
6. Pads : remove SiO_2 by wet-etching

5 x deposition, 5 x etching, 5 x e-beam, 1 x lift off, 1 x opt. lithography

11 layer process : very good yield !

Technology : large circuits

2 x 6000 JJ : double-stacked
JJ-size : 4.0 µm x 11.0 µm



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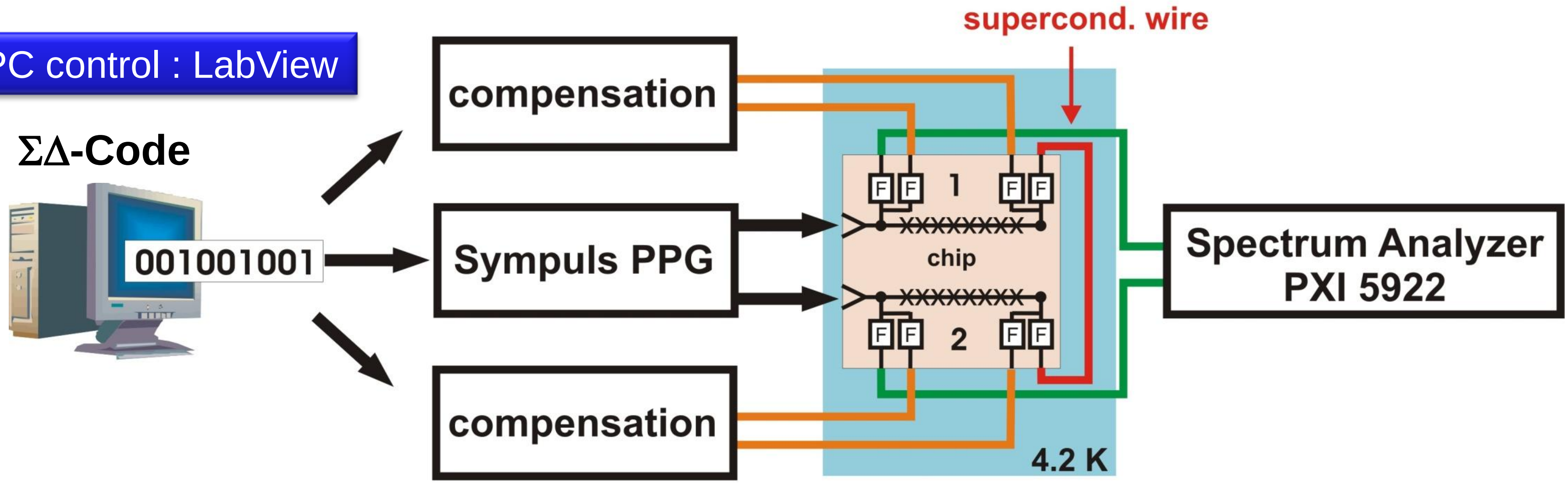
setup : 2 arrays in series @ 1 chip

PC control : LabView



Sympuls PPG :
- ternary pulses : -1 / 0 / +1
- 2 output channels
- max. clock-frequency : 15 GHz
- max. code-memory : 256 Mbit

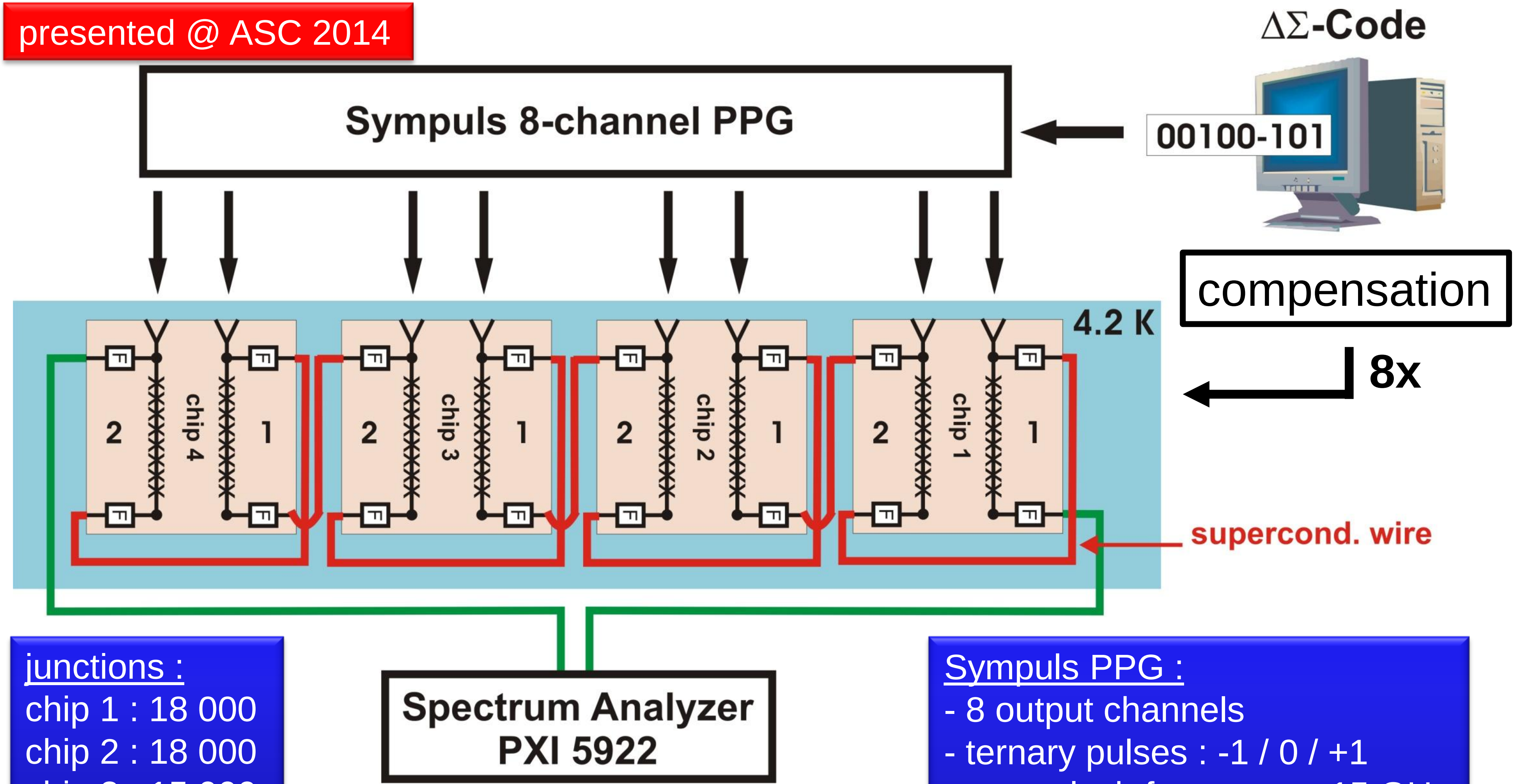
„pure“ spectra, if optimized :
- ΣΔ-codes
- experimental setup
- broadband Josephson arrays

2 JAWS systems operational @ PTB

AC-coupling technique: S. P. Benz, et al., *IEEE Trans. Appl. Supercond.* 11, March 2001

setup : 8 arrays in series @ 4 chips

presented @ ASC 2014



junctions :
chip 1 : 18 000
chip 2 : 18 000
chip 3 : 15 000
chip 4 : 12 000

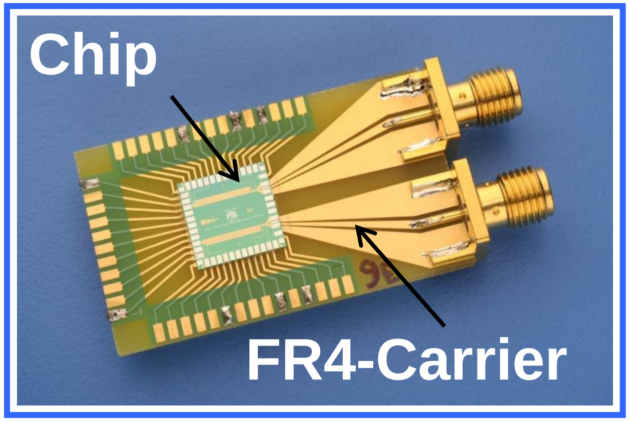
Sympuls PPG :
- 8 output channels
- ternary pulses : -1 / 0 / +1
- max. clock-frequency : 15 GHz
- max. code-memory : 256 Mbit
- bit multiply-function

cf. : Kieler et al., *IEEE Trans. Appl. Superc.* 2015

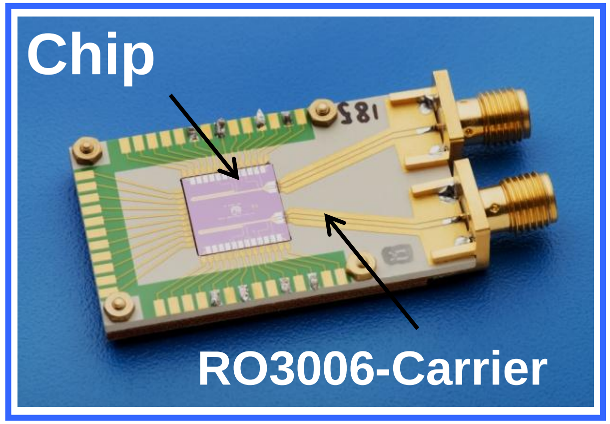
JAWS : optimization of chip-carrier

new

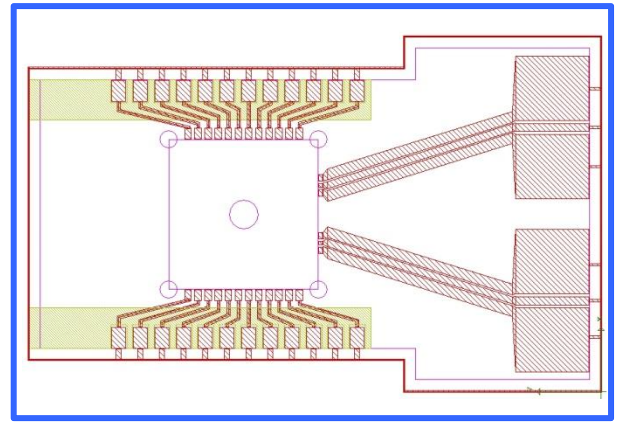
1. generation	2. generation	3. generation



- Chips size : 10 mm x 10 mm
- 2 HF-CPW and > 40 LF leads
- PCB : FR4



- optimized HF-CPW leads
- optimum PCB material (simulations 2.22 K. Kuhlmann)



- parallel-operation of 4 carriers
- no back-plate necessary (operation in cryocooler ?)

new carriers in operation successfully

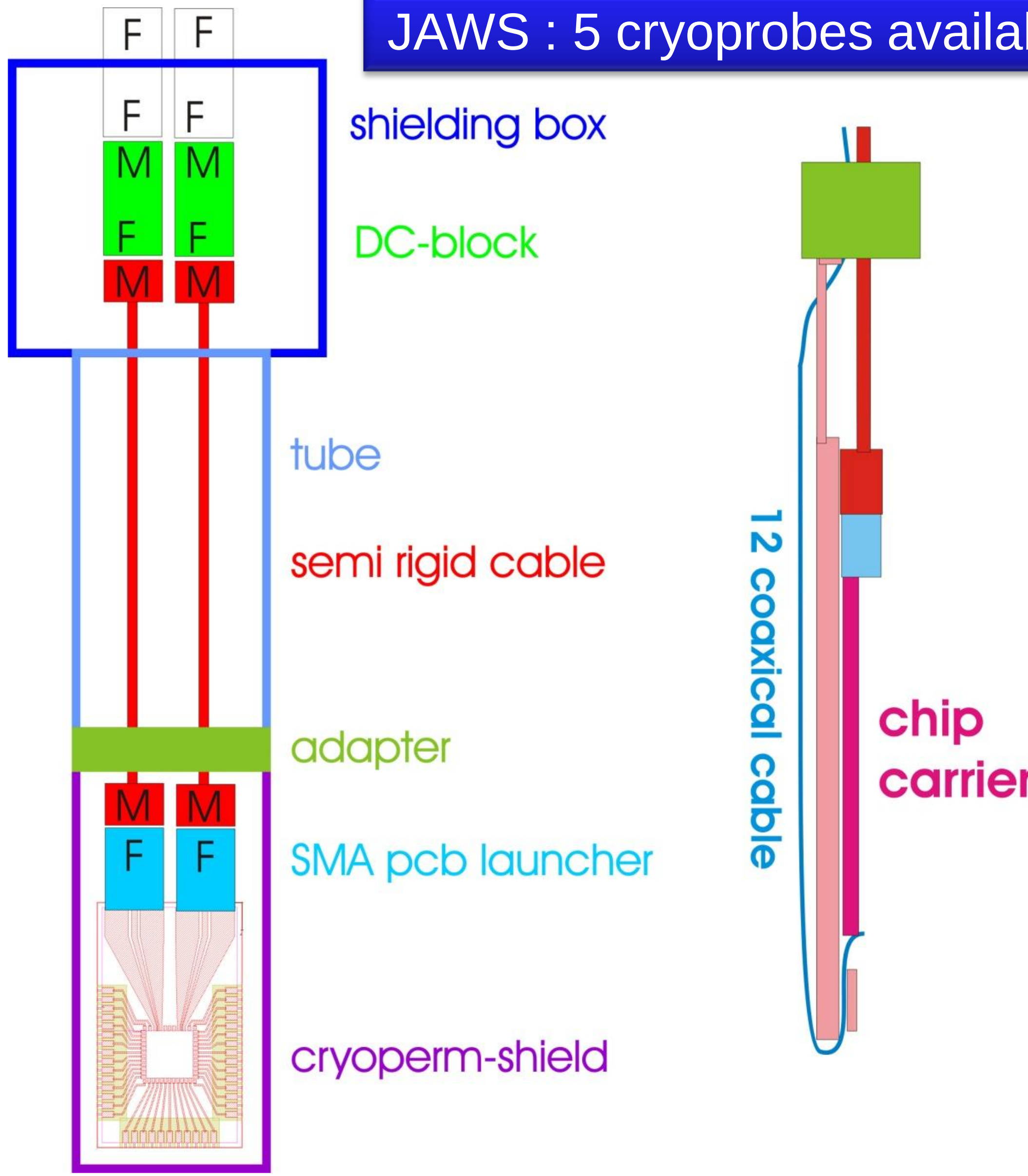
JAWS : example of a cryoprobe

cryoprobe parameter :

- dc-blocks in probe head (ac-coupling)
- broadband (> 18 GHz)
- shielded
- floating
- length : about 1 m

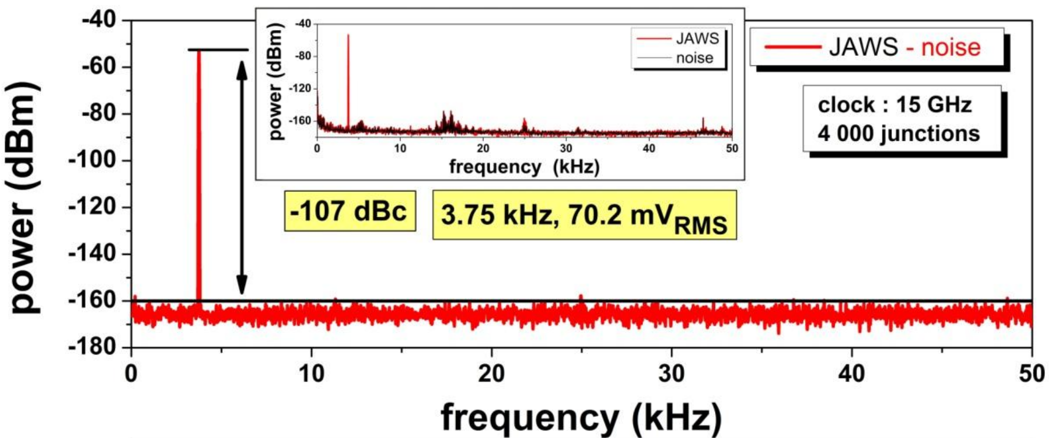
„pure“ spectra, if experimental setup is optimized !

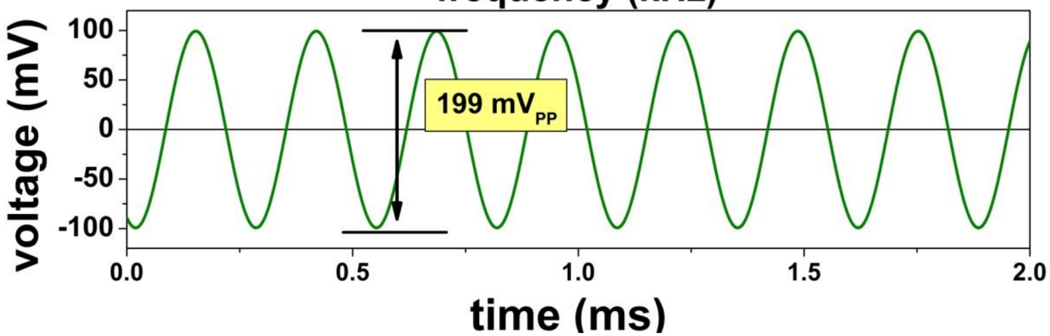
JAWS : 5 cryoprobes available

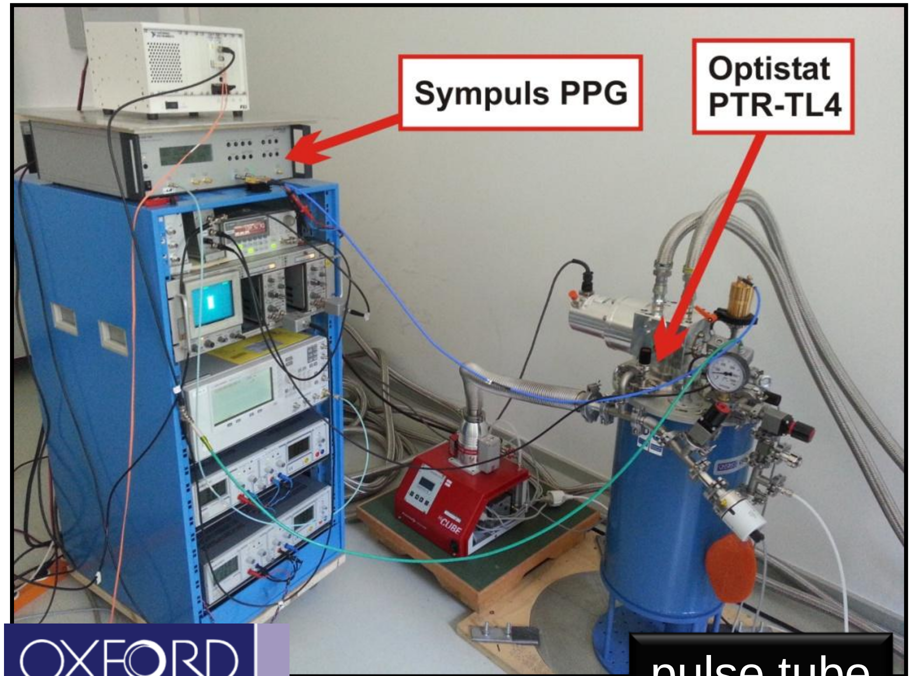


JAWS : cryocooler operation (I)

- spectra up to voltages of ≈ 200 mV_{pp} with 4 000 junctions
- temperature range : 4.2 K to 5.6 K







successful operation of JAWS in cryocooler

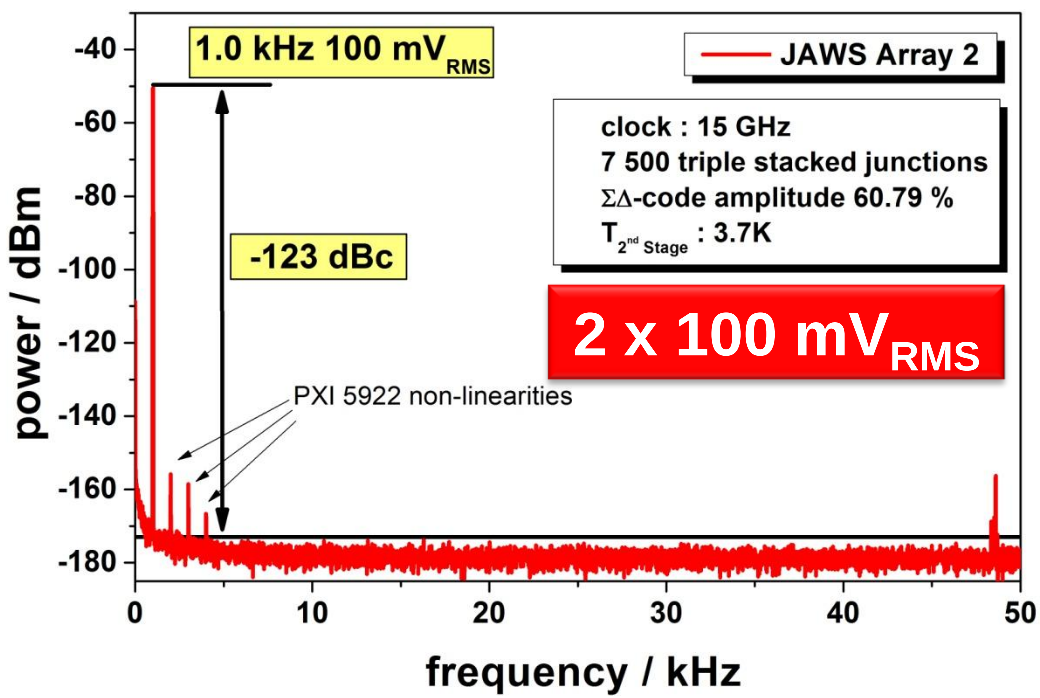
AIST[2] :
2.6 mV_{pp} with 100 junctions,
SNR -80 dBc

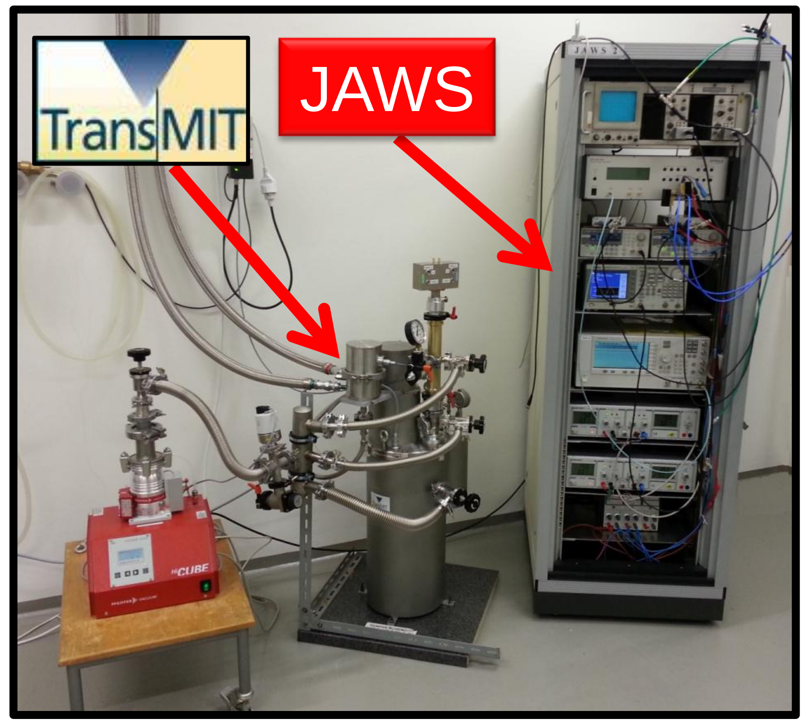
[2]Urano et al., *SUST* 22, Oct. 2009

cf. : Kieler et al., *W. Journal Cond. Matter Physics* 3, Nov. 2013

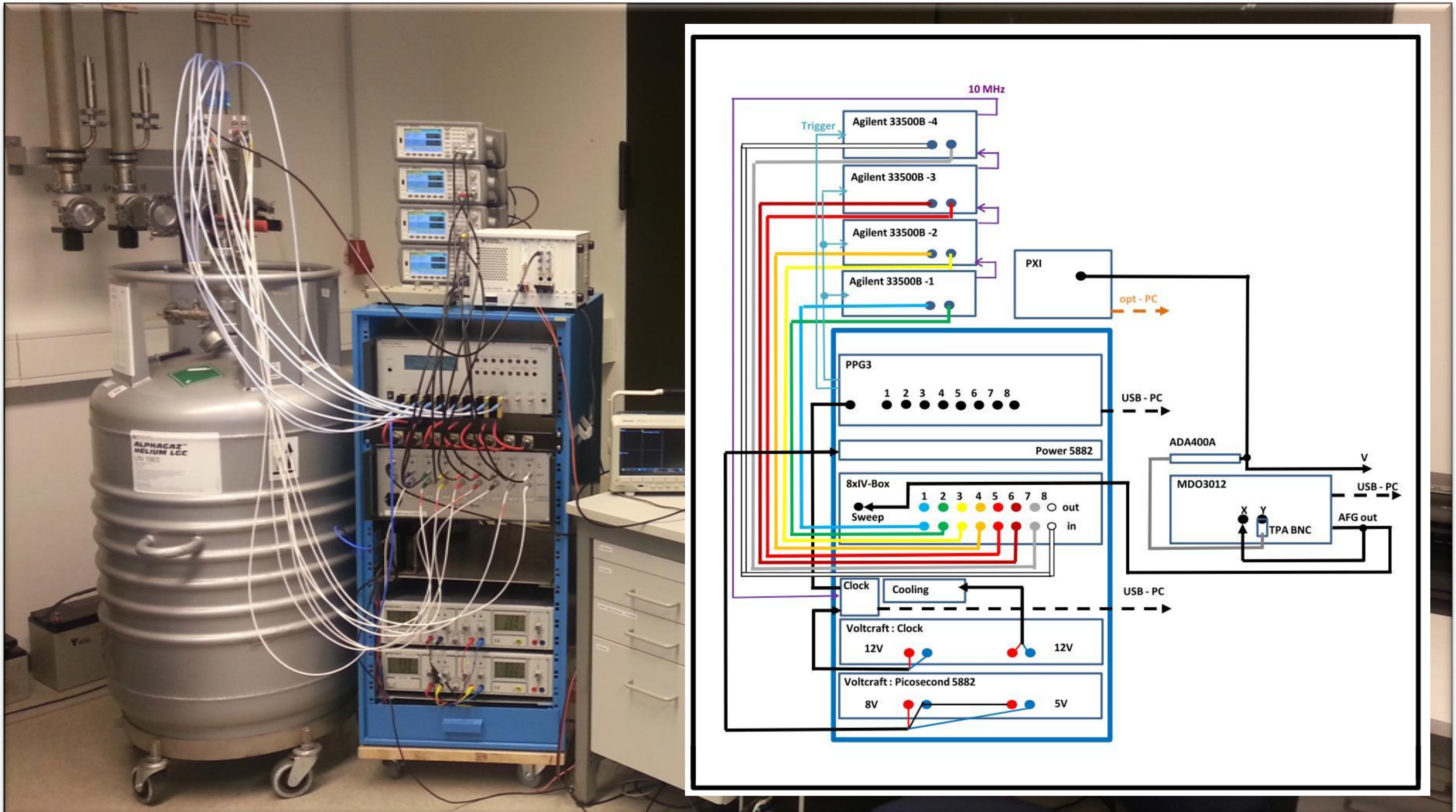
JAWS : cryocooler operation (II)

- **JAWS-system** : - fully operational
  - 2 array @ 1 chip : 2 x 100 mV_{RMS}
  - pure spectra and noise floor
- **cryocooler** : - made by TransMIT
  - pulse-tube
  - optimized thermal and electrical coupling
- **EMRP „AIM-QuTE“** : - impedance-bridge measurements





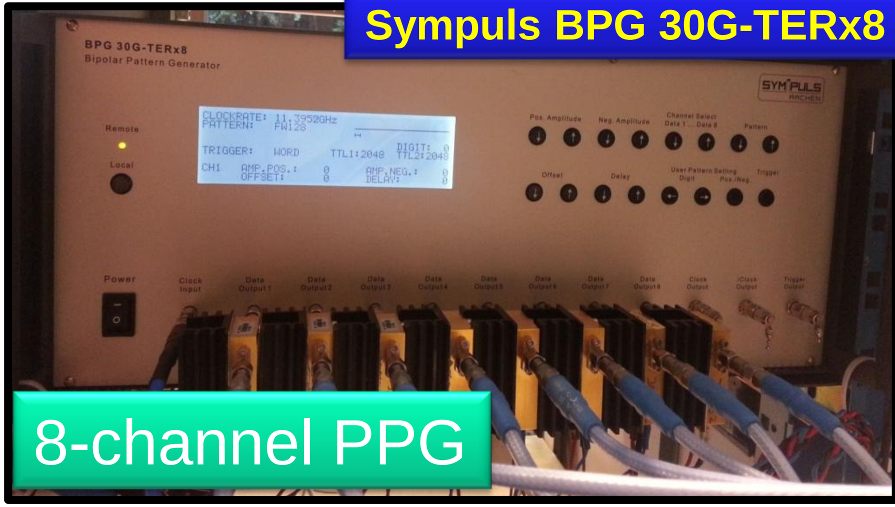
setup : JAWS 1 V system (I)



cf. : Kieler et al., *IEEE Trans. Appl. Superc.* 2015

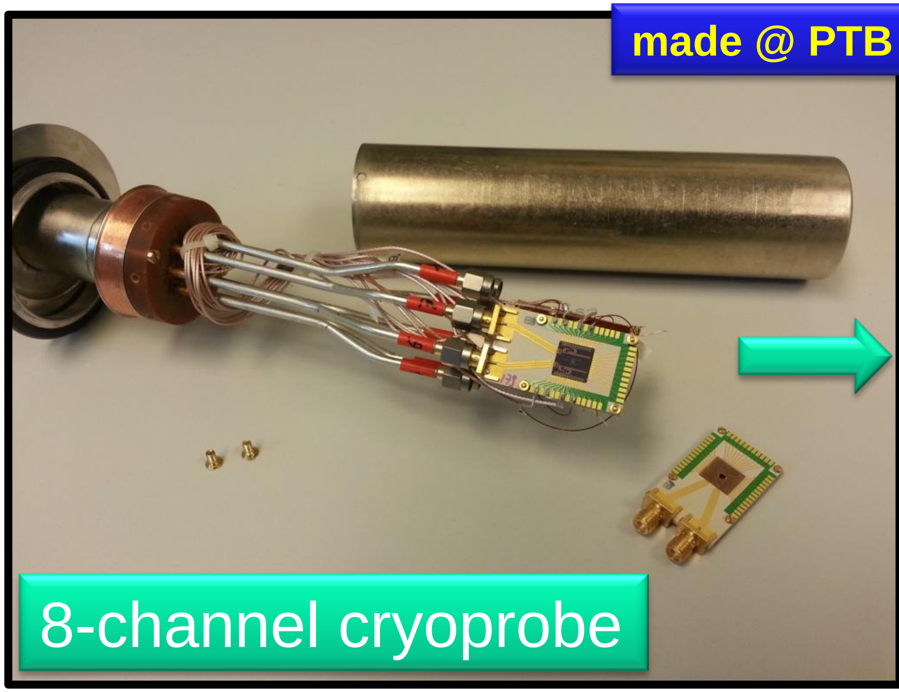
setup : JAWS 1 V system (II)

Sympuls BPG 30G-TERx8



8-channel PPG

made @ PTB



8-channel cryoprobe

compensation:

made @ PTB

8-channel „IV-Box“

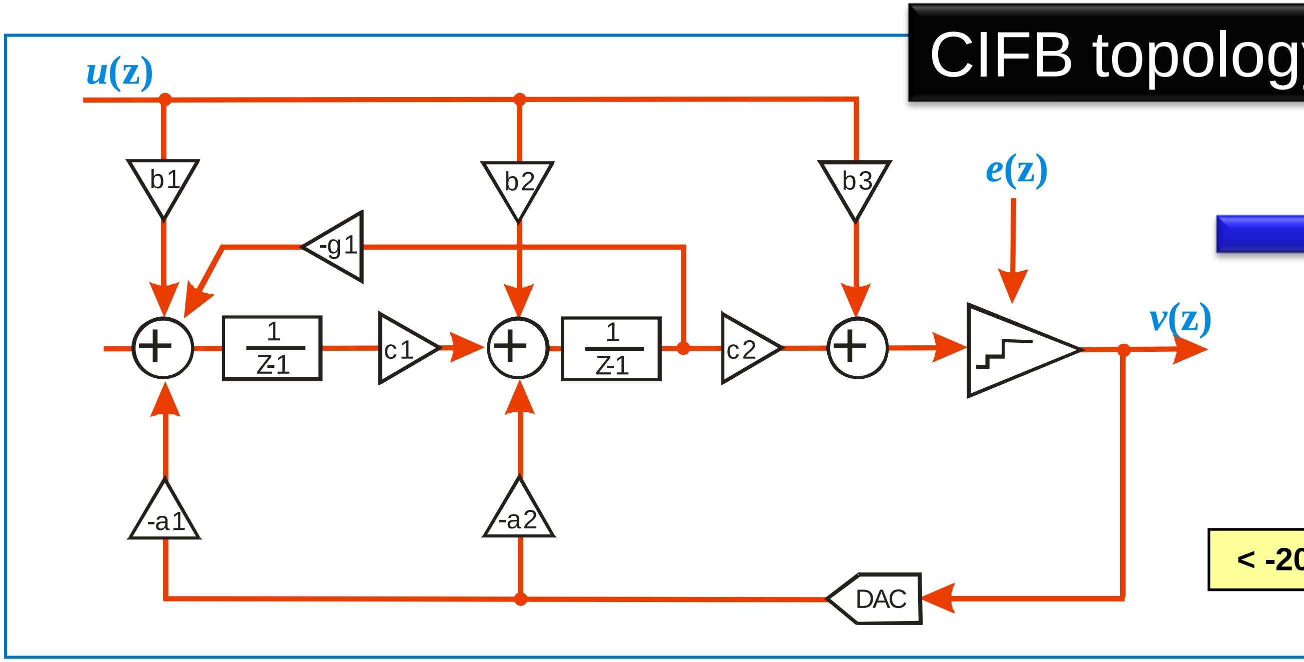
Agilent 33522B

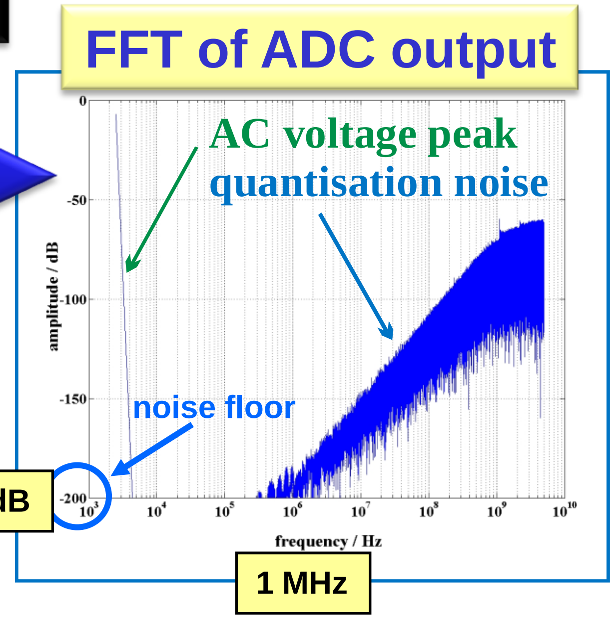
4 x 2-channel waveform synthesizer

features :

- pulse : 8 semi-rigid HF-cable
- voltage : 1…4 coaxial cable
- compensation : 8 coaxial cable
- series arrays : 7 superconducting cable

pulse-code : ΣΔ-modulation (I)





ΣΔ-modulator topology[1] **:**

- 2nd order modulator
- cascade of integrators
- feedback form
- delays included
- optimized coefficients a/b/c/g[2]
  - NTF(*f*) = 1 , i.e. no voltage error by code itself
  - maximum theoretical SNR = -123 dBc
  - calculated $SNR_{expected}$ = -115...-119 dBc (sinc^3 - filter)

modulator output : $v(z) = STF \cdot u(z) + NTF \cdot e(z)$

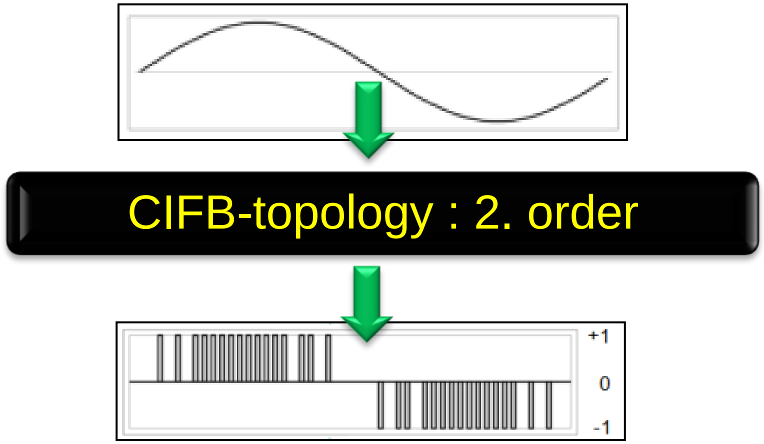
signal-transfer function : $STF = \left[\dfrac{b_3 \cdot z^2 + (c_2 b_2 - 2b_3) \cdot z + (b_3^2 + b_3 c_1 g_1 - c_2 b_2 + c_1 c_2 b_1)}{z^2 + (c_2 a_2 - 2) \cdot z + (1 + c_1 g_1 - c_2 a_2 + c_1 c_2 a_1)} \right]$

noise-transfer function : $NTF = \left[\dfrac{z^2 - 2z + (1 + c_1 g_1)}{z^2 + (c_2 a_2 - 2) \cdot z + (1 + c_1 g_1 - c_2 a_2 + c_1 c_2 a_1)} \right]$

code stored in memory of PPG

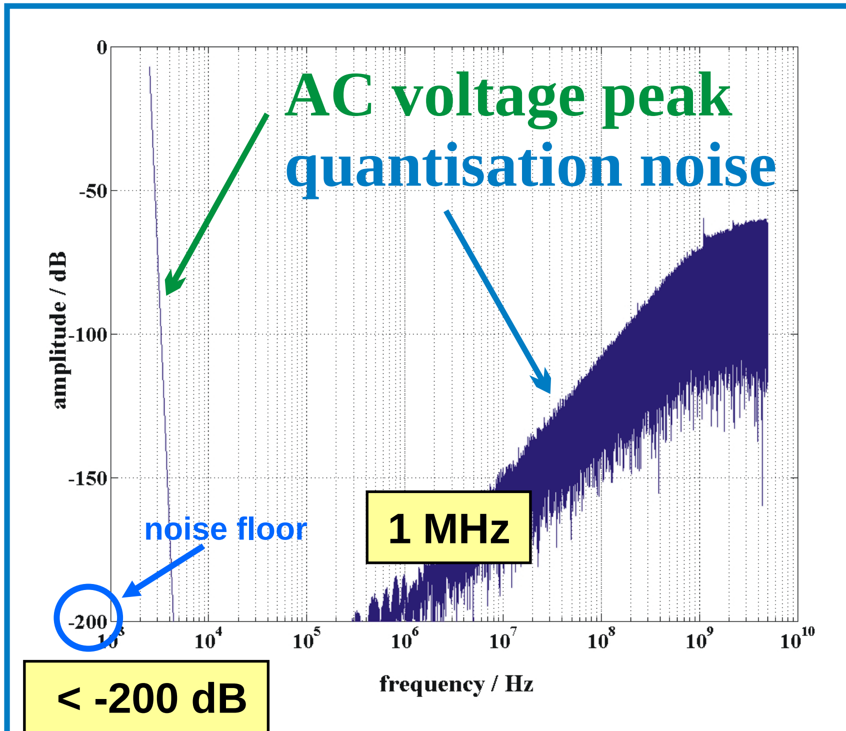
[1] R. Schreier, G. Temes, IEEE Press, J.-Wiley and Sons, Inc., New Jersey, 2005
[2] Matlab® : The MathWorks, Inc., Delta-Sigma Toolbox

pulse-code : ΣΔ-modulation (II)



$f_{signal} = T_{code} \times f_{clock} / L_{PPG}$

FFT



multi-core server : ZUSE

PPG max. code-length : 256 Mbit

ΣΔ-code : transmission to PPG !

[1] R. Schreier, G. Temes, IEEE Press, J.-Wiley and Sons, Inc., New Jersey, 2

[2] Matlab® : The MathWorks, Inc., Delta-Sigma Toolbox

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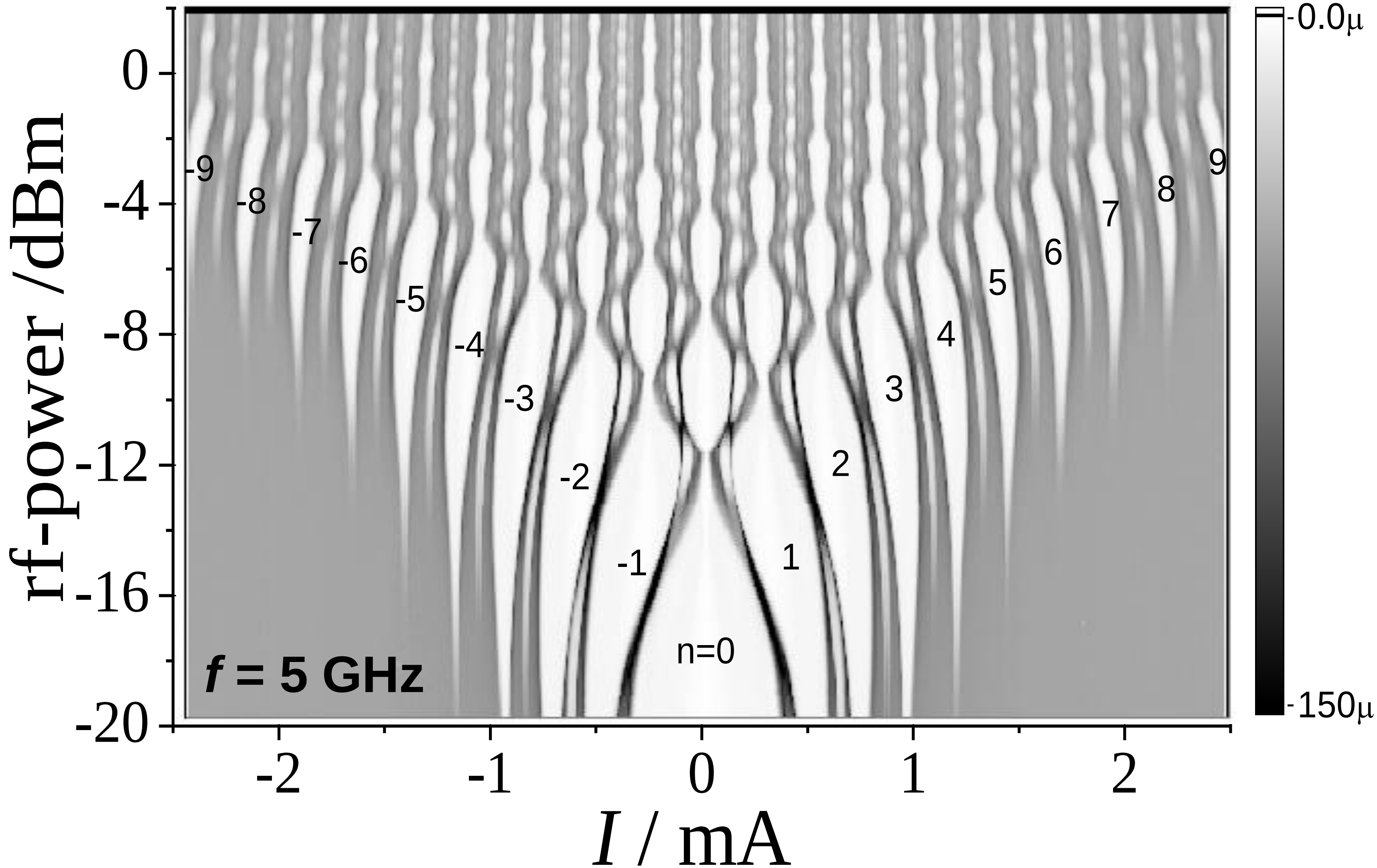
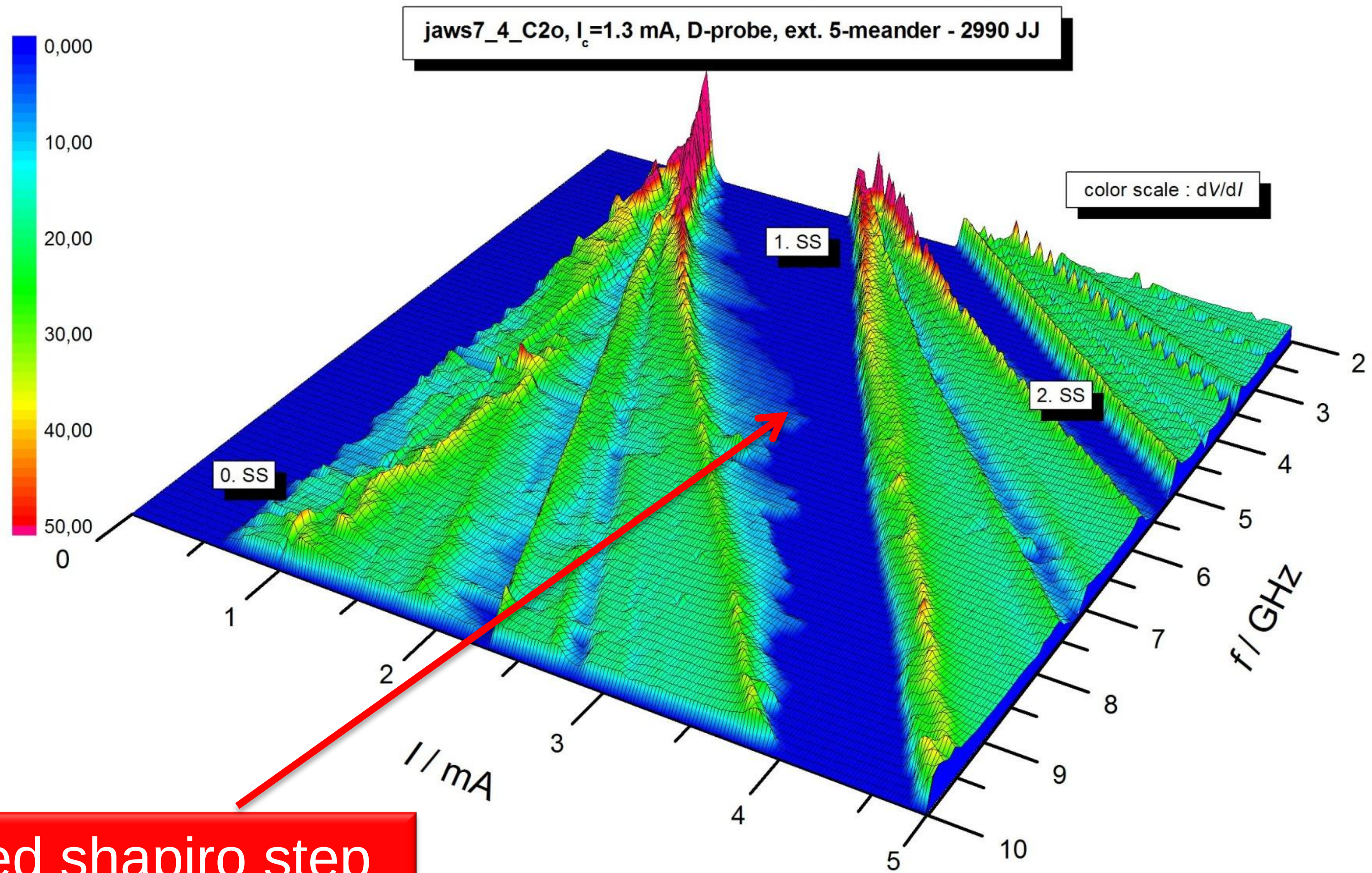
JAWS : broadband (I)

512 junctions



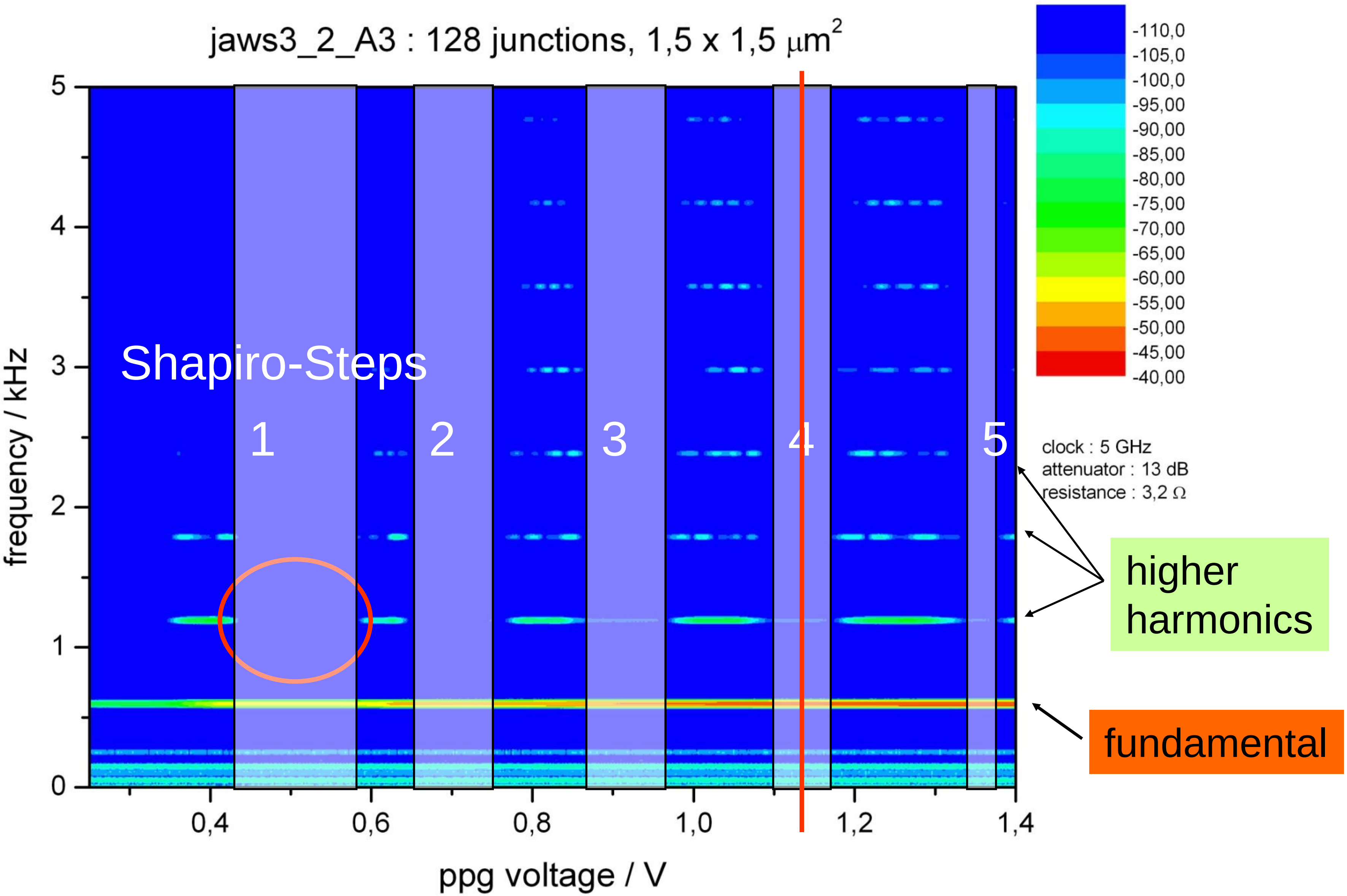
JAWS : broadband (II)

current-votlage-characteristic vs. frequency (power adjusted)



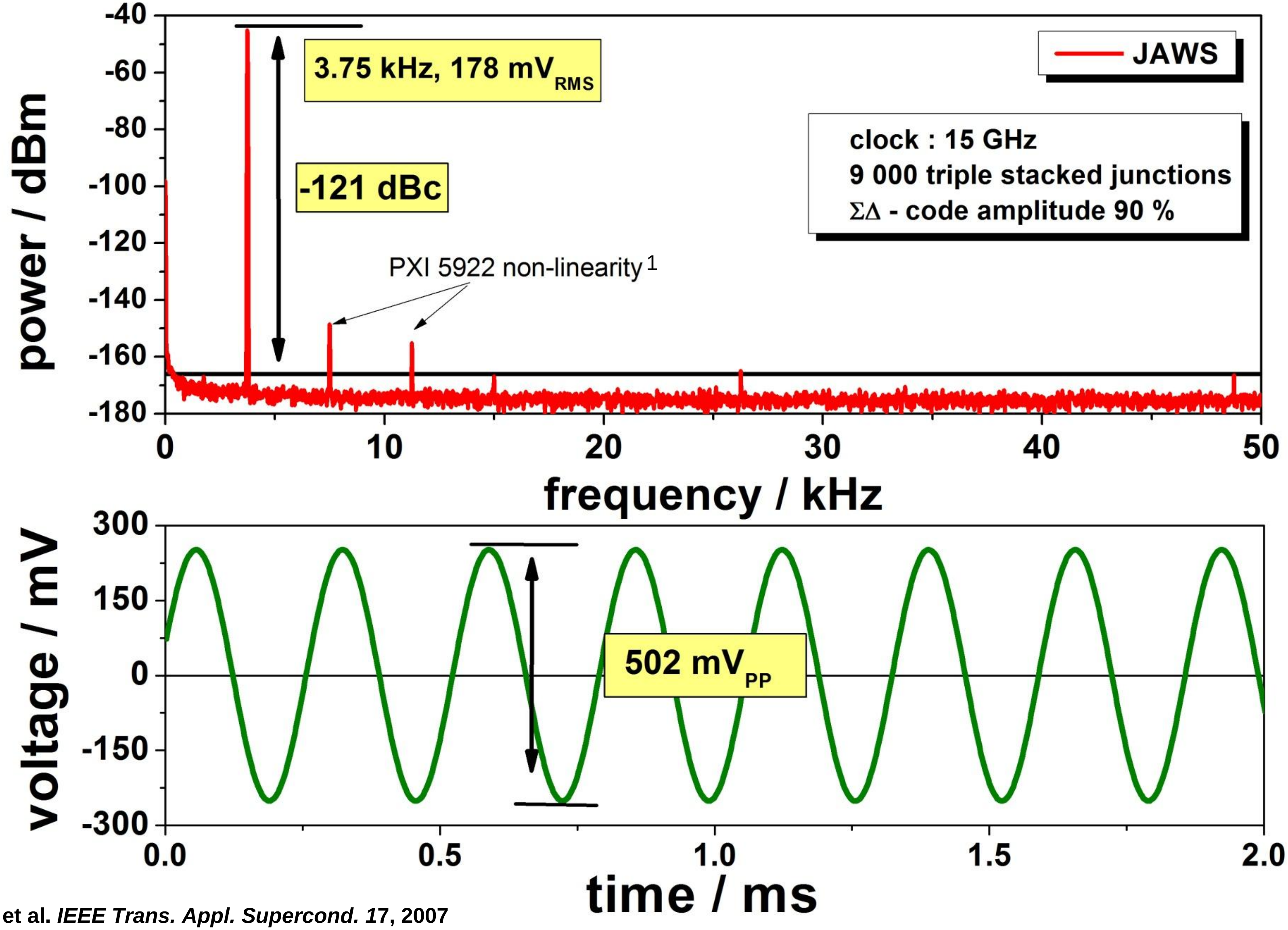
reduced shapiro step

JAWS : broadband (III)



triple-stacked junctions : 1 array

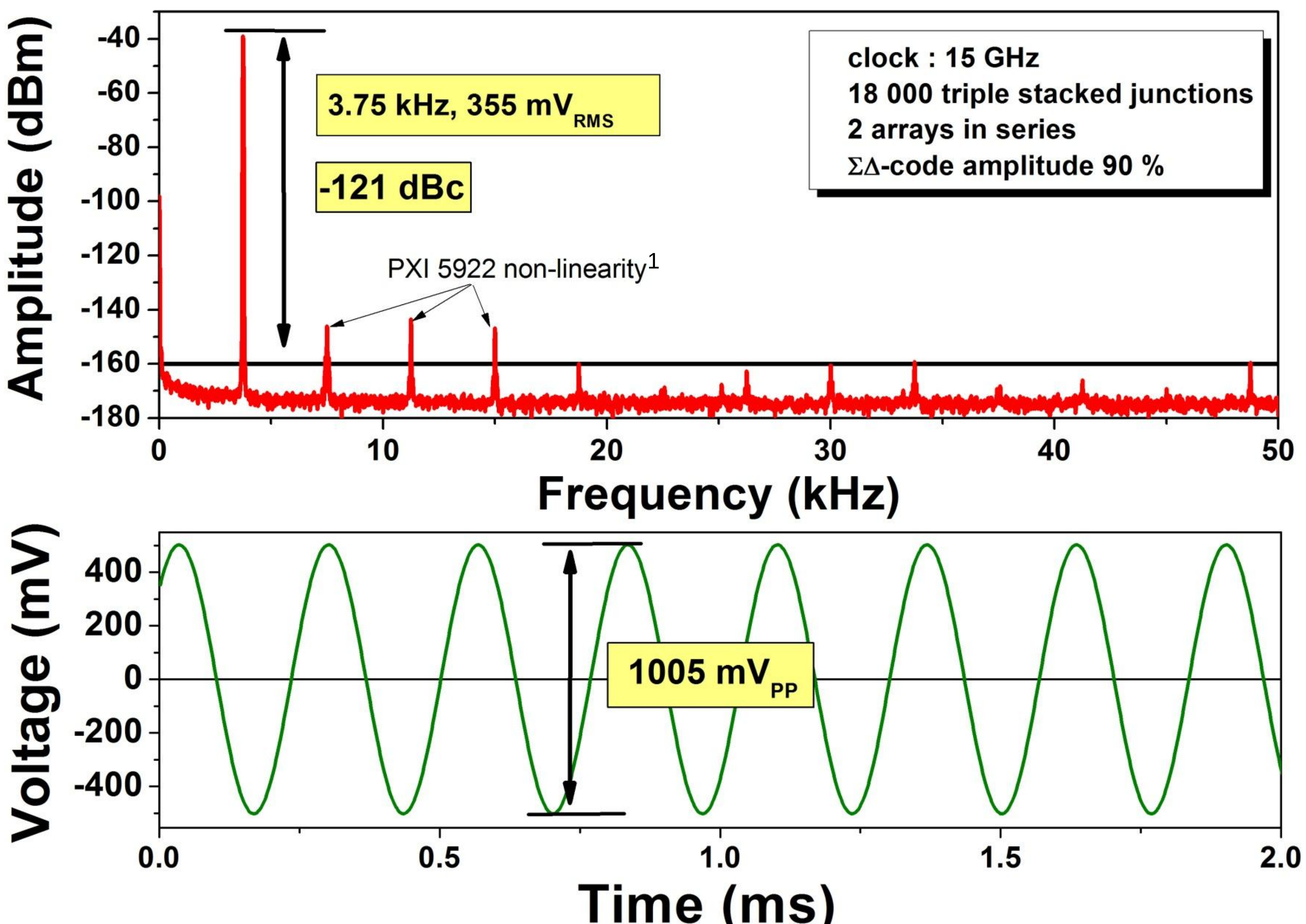
- spectra up to voltages of 502 mV_{pp} with 9 000 junctions



[1]S. P. Benz, et al. *IEEE Trans. Appl. Supercond. 17*, 2007

triple-stacked junctions : 2 arrays @ 1 chip

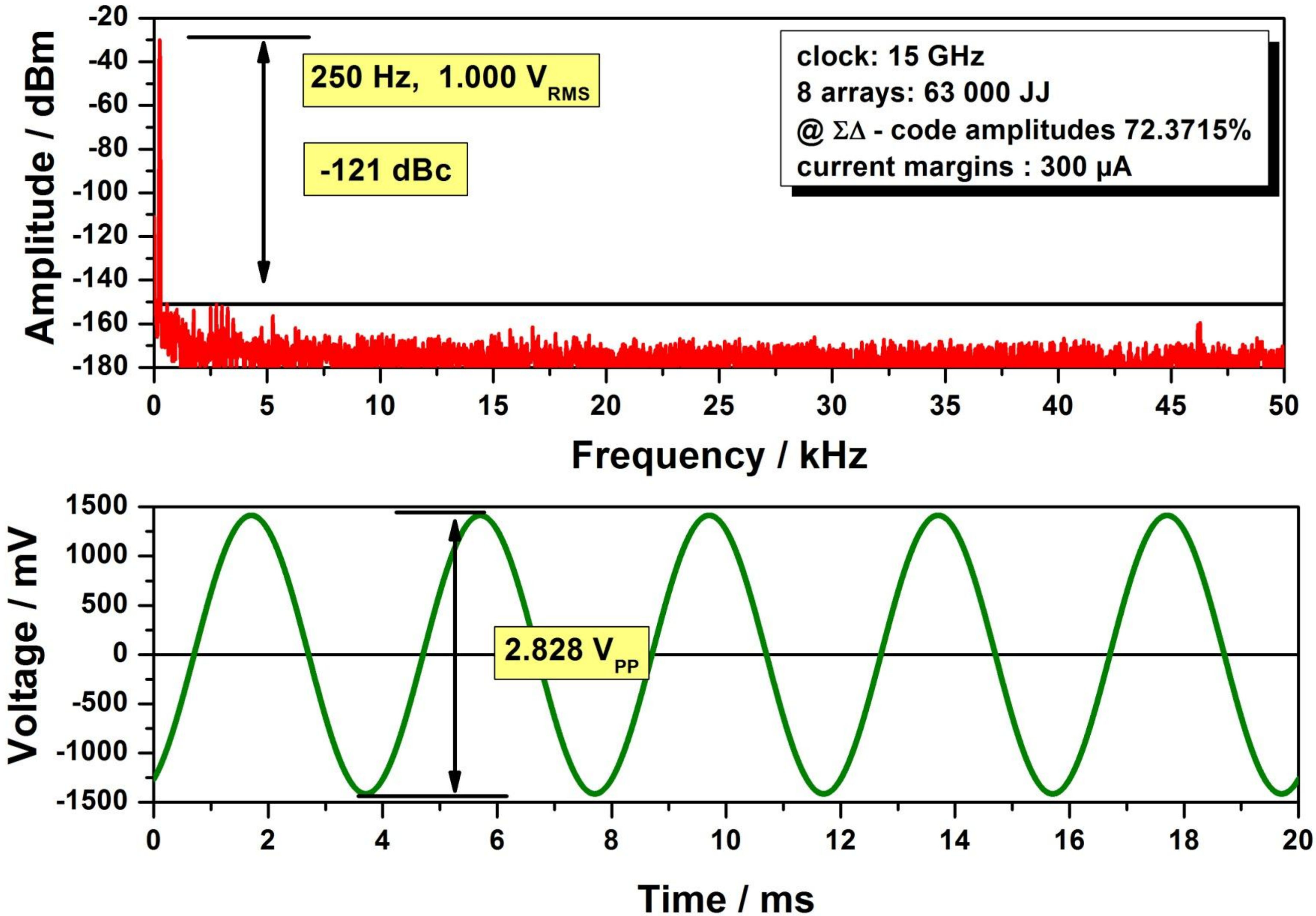
➢ spectra up to voltages of 1005 mV_{pp} with 18 000 junctions



[1]S. P. Benz, et al. *IEEE Trans. Appl. Supercond. 17*, 2007

triple-stacked junctions : 8 array @ 4 chips

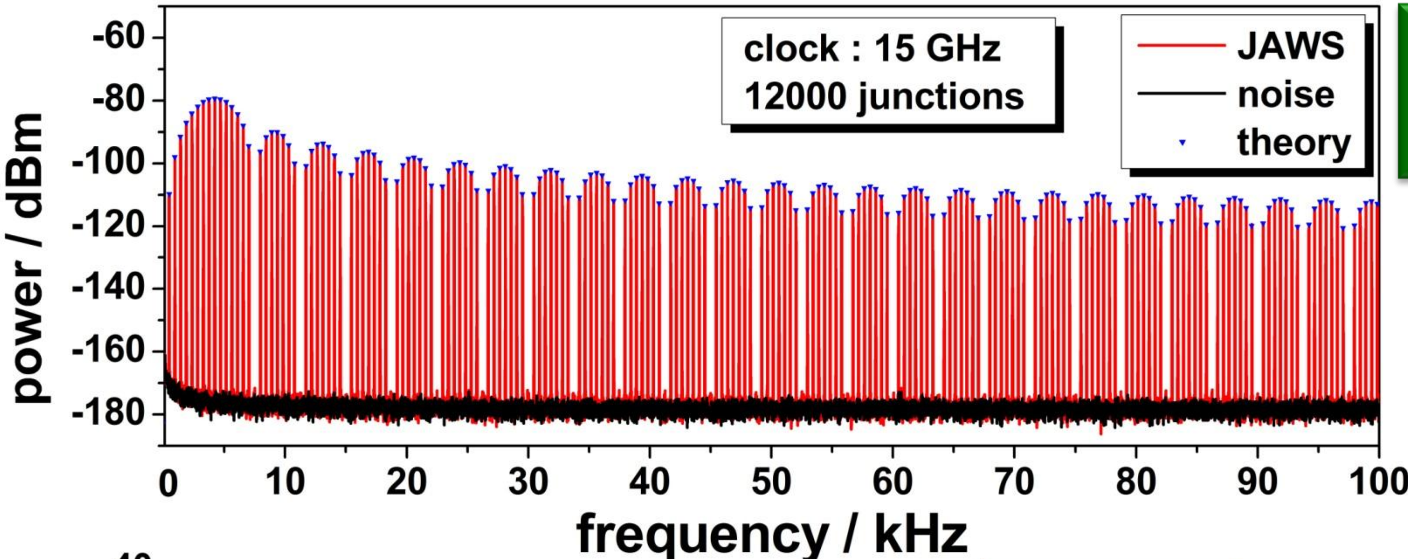
➢ spectra up to voltages of 1.0 V_{RMS} (2.8 V_{pp}) with 63 000 junctions



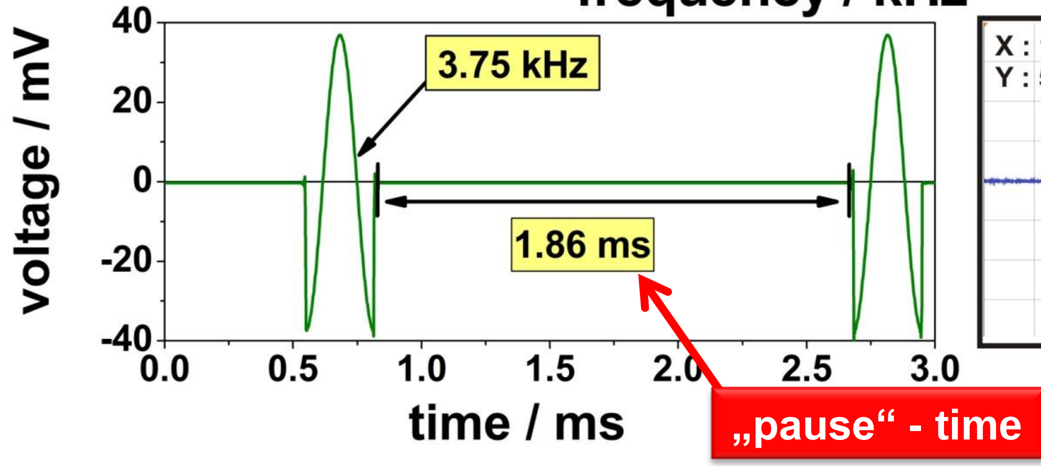
special waveforms (I)

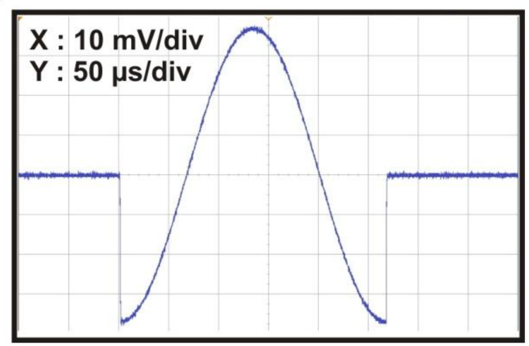
characterization AD-converter (e.g. „single-shot“)

➢ **non-continuous waveform : cosines with „pause“- time**



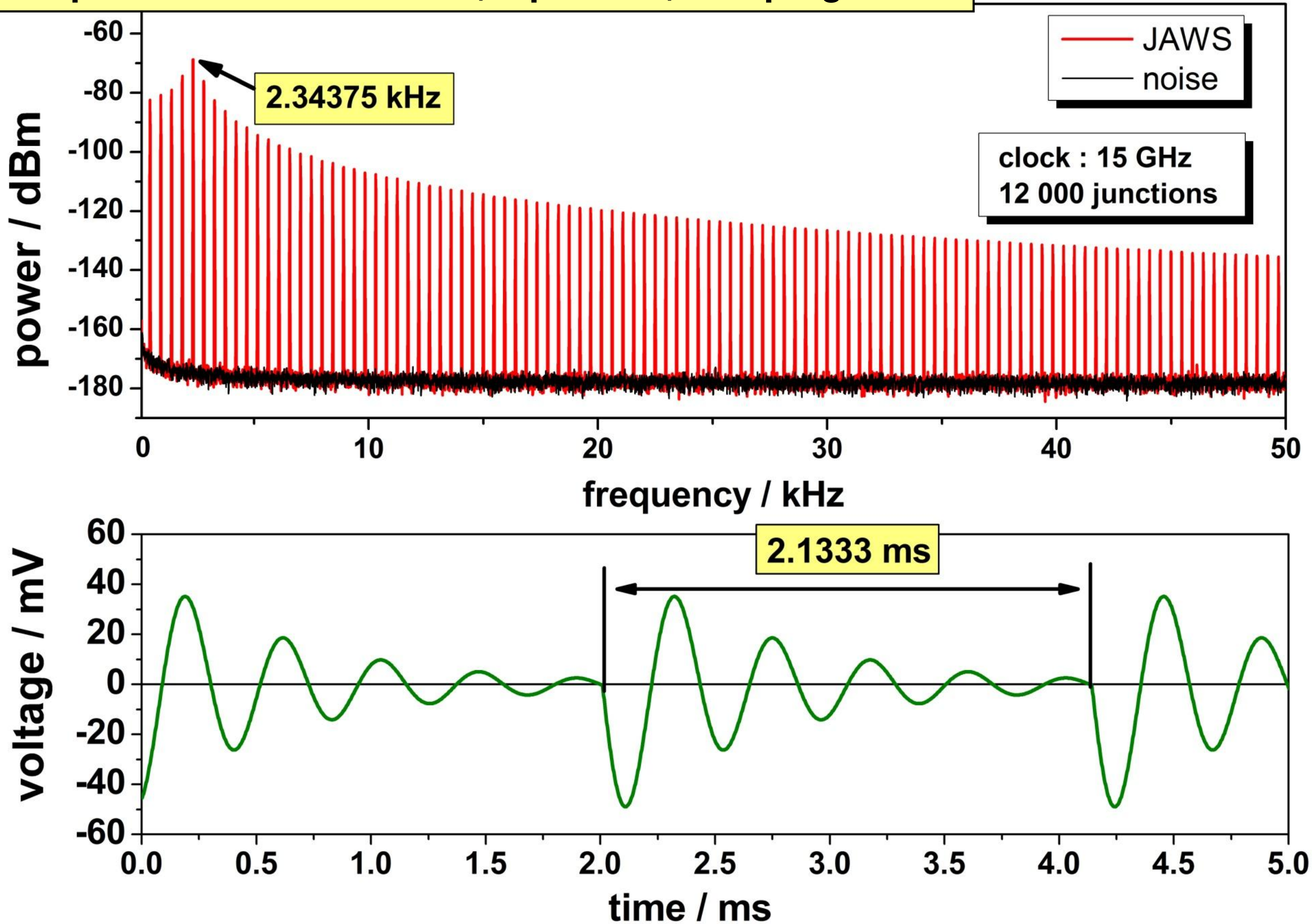
JAWS :
most suitable





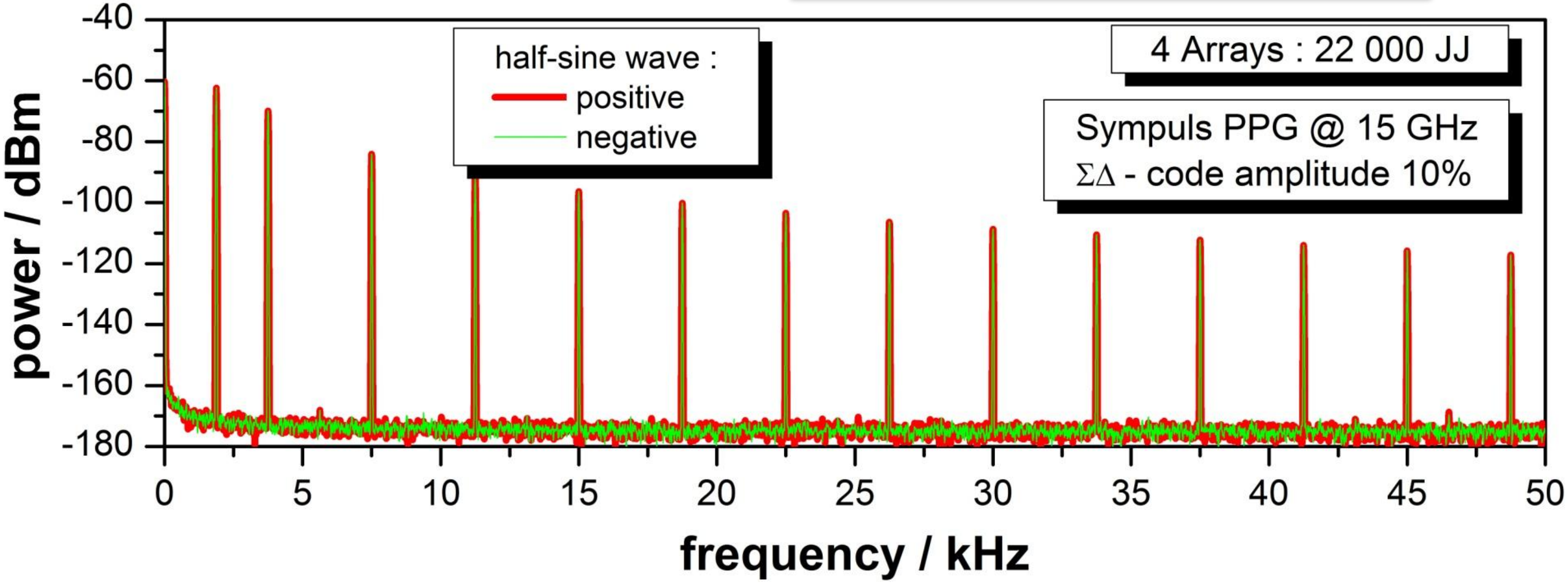
special waveforms (II)

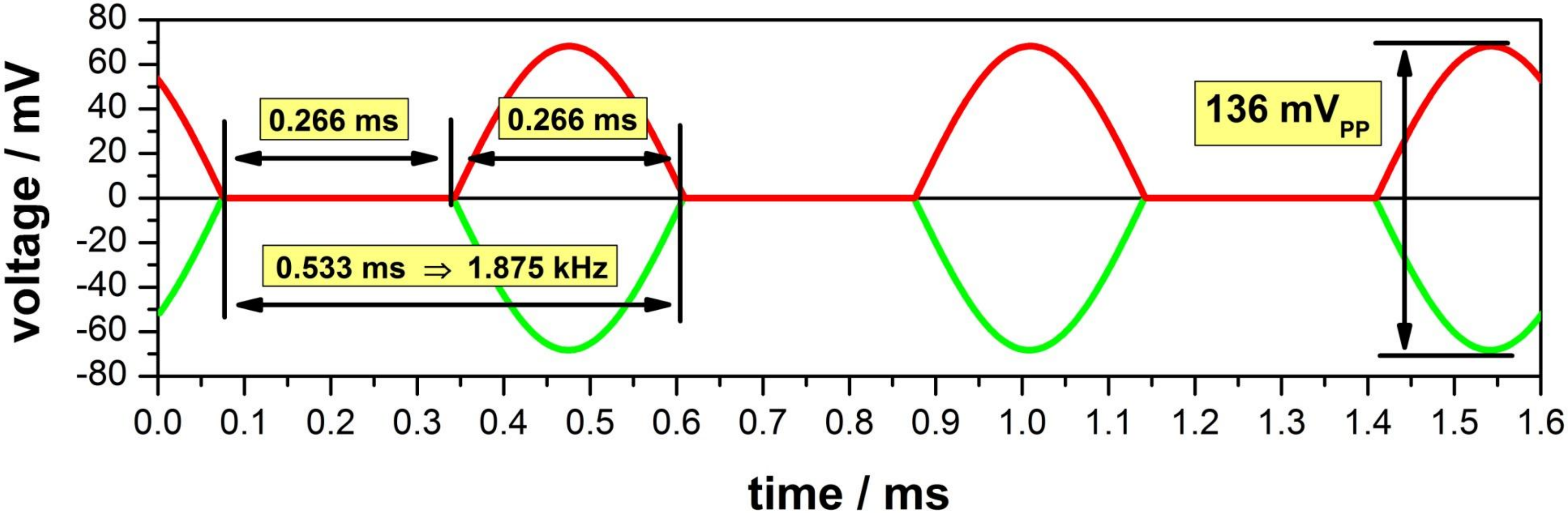
- damped waveforms : sinus, 5 periods, damping -3 dB



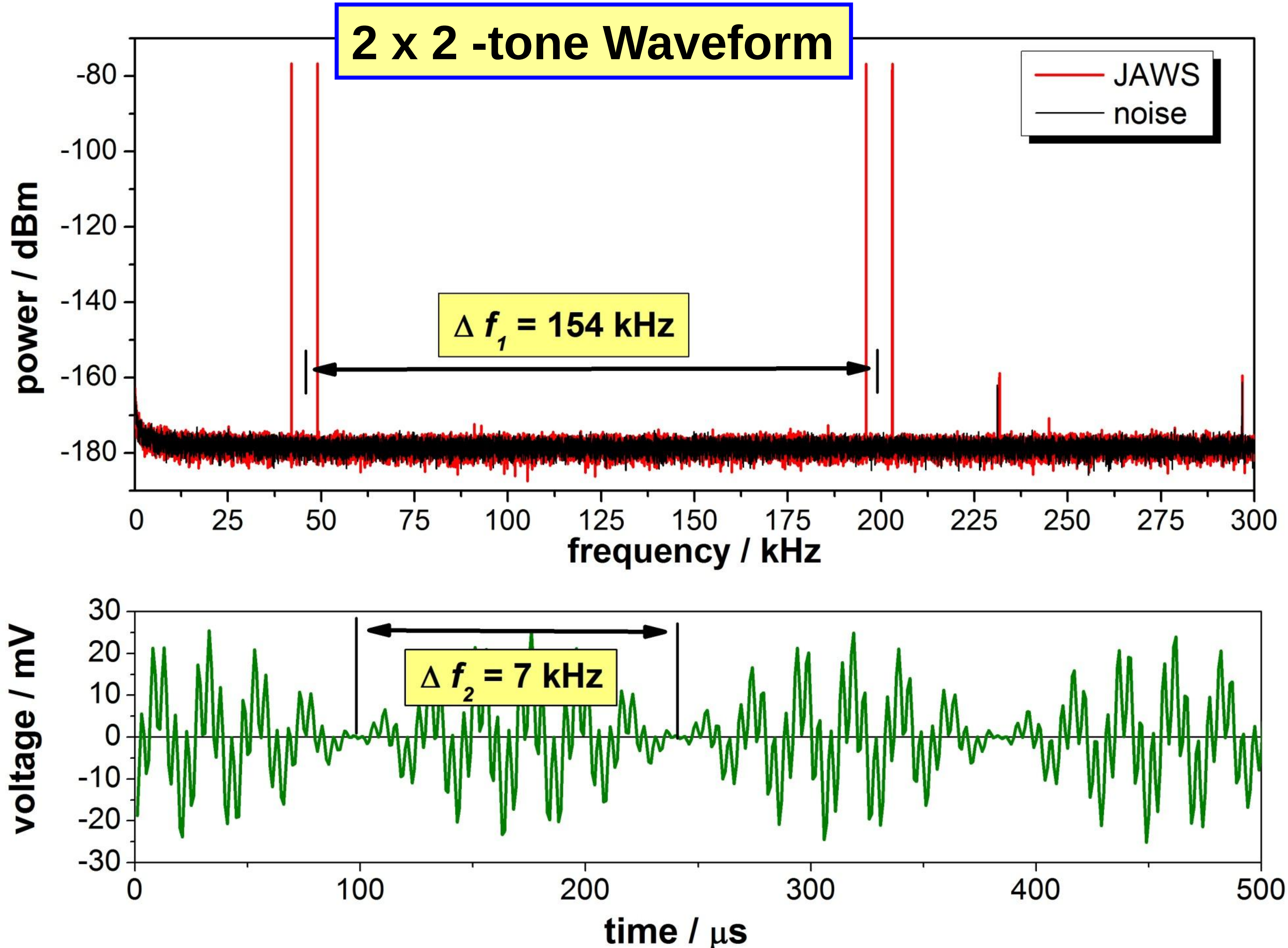
special waveforms (III)

- „half"- waveform : sinus → undistinguishable in spectrum

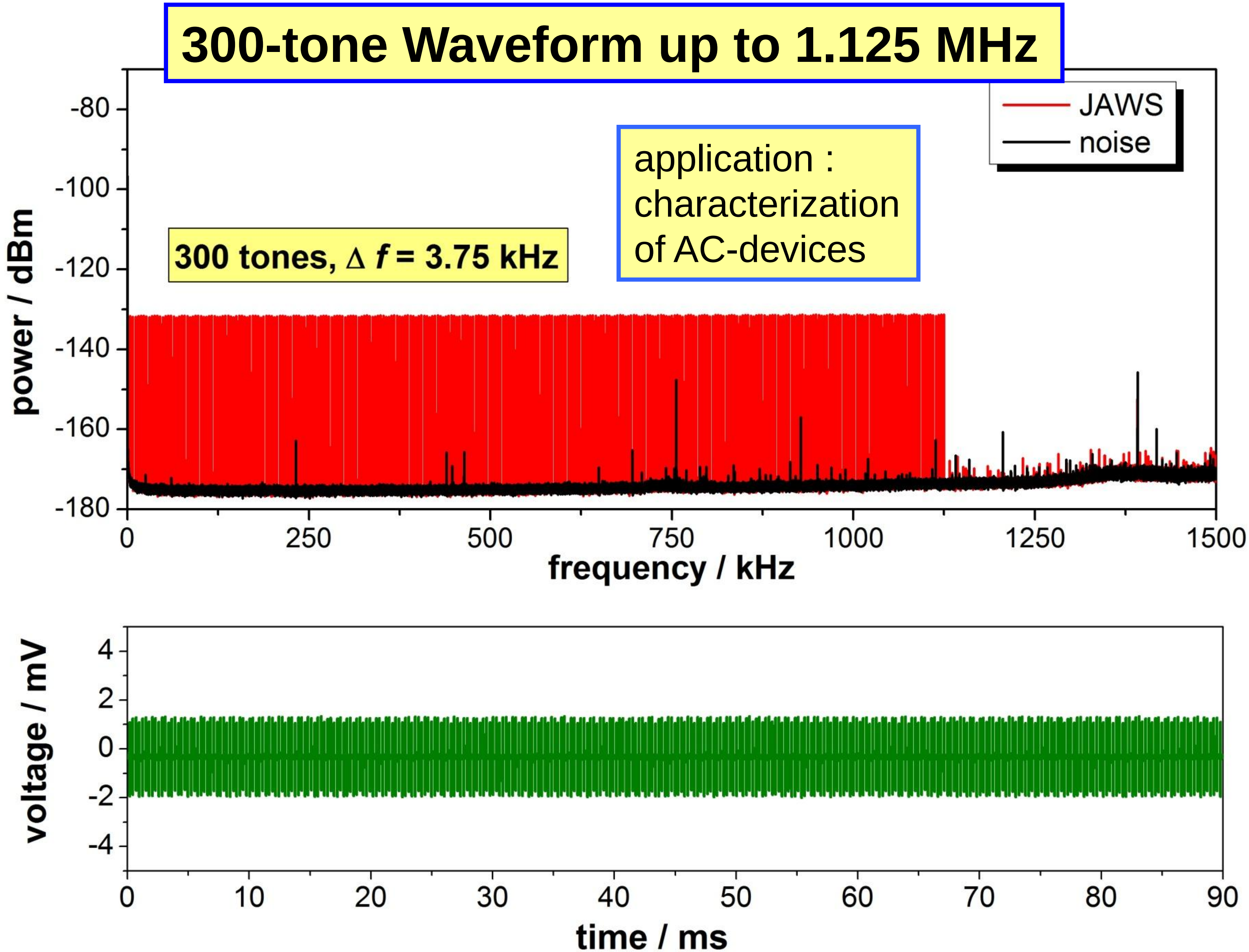




special waveforms (IV)

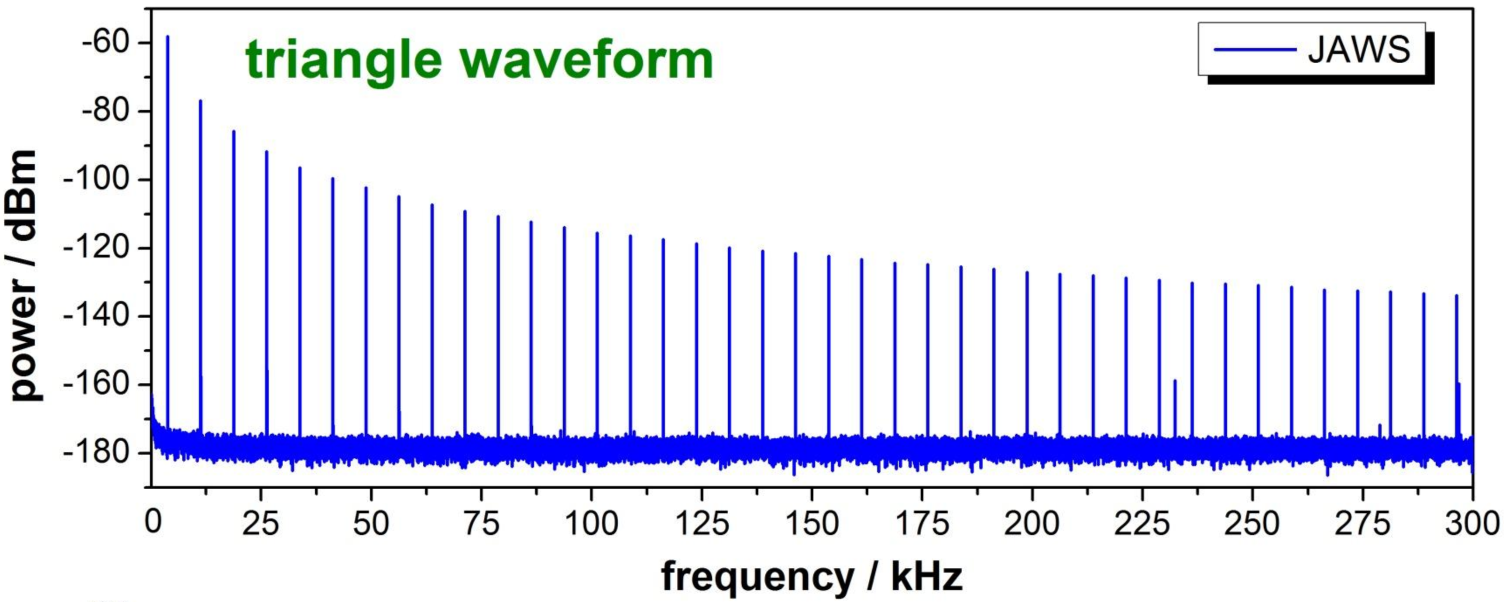


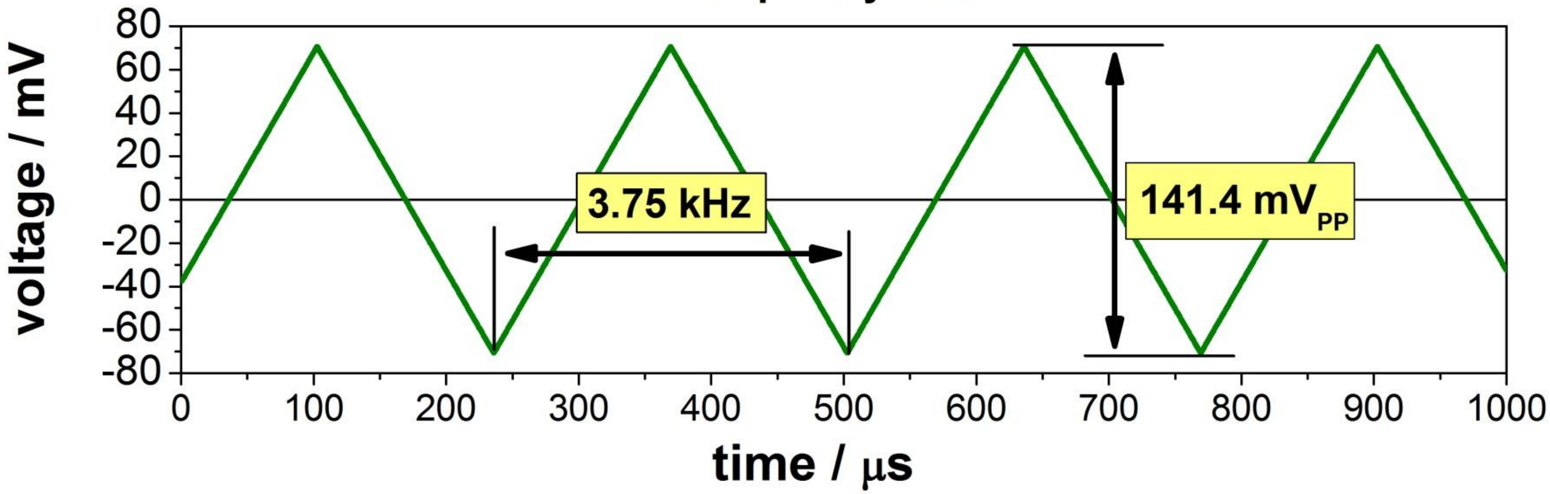
special waveforms (V)



special waveforms (VI)

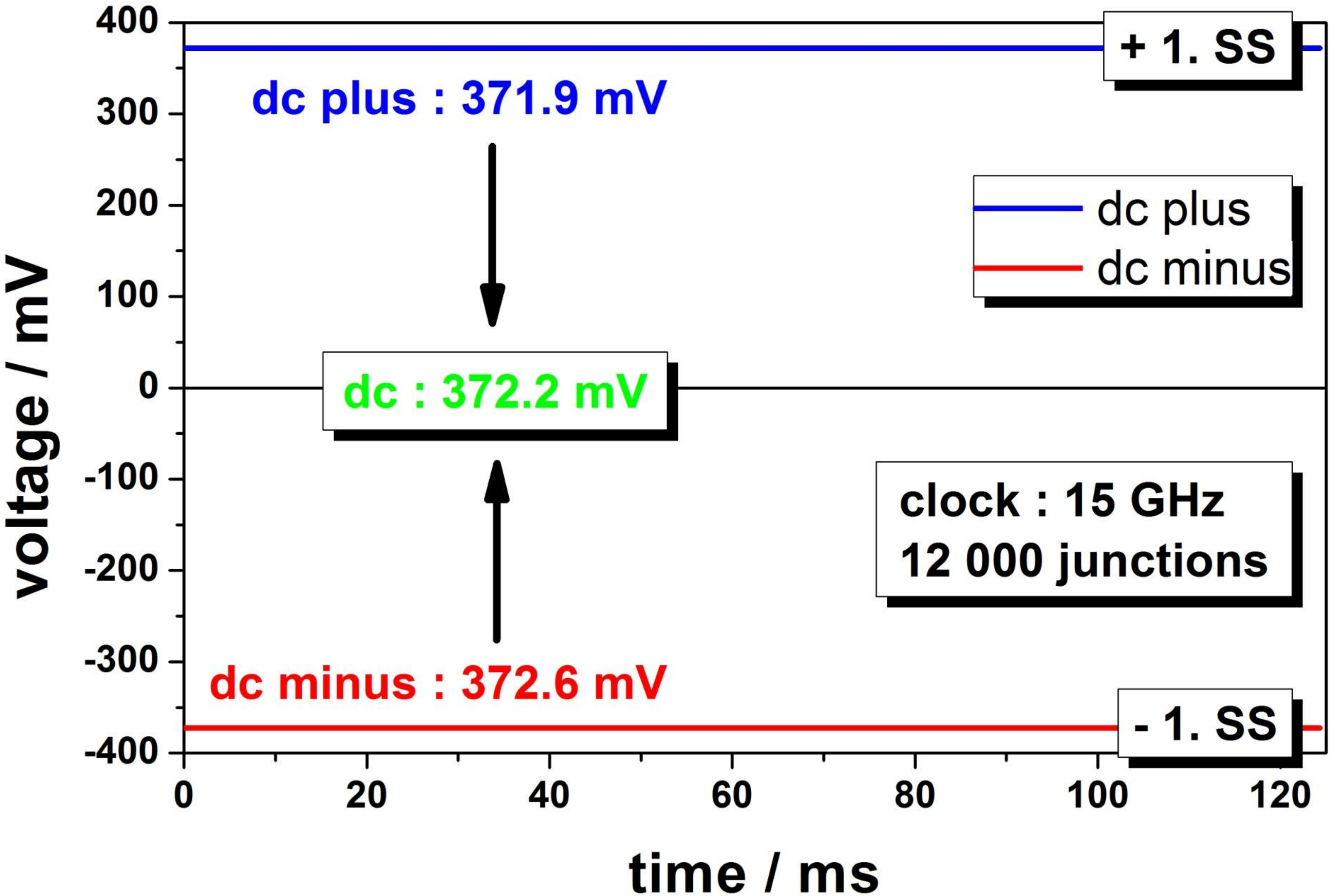
common waveform : triangle



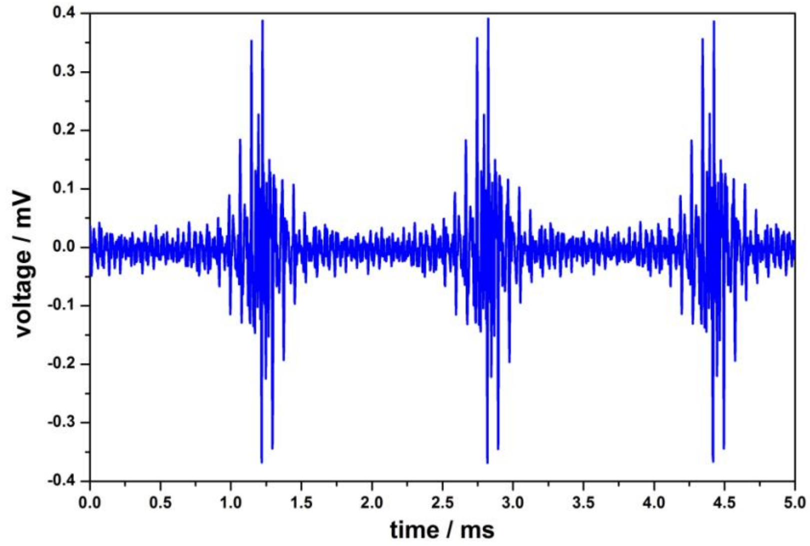


special waveforms (VII)

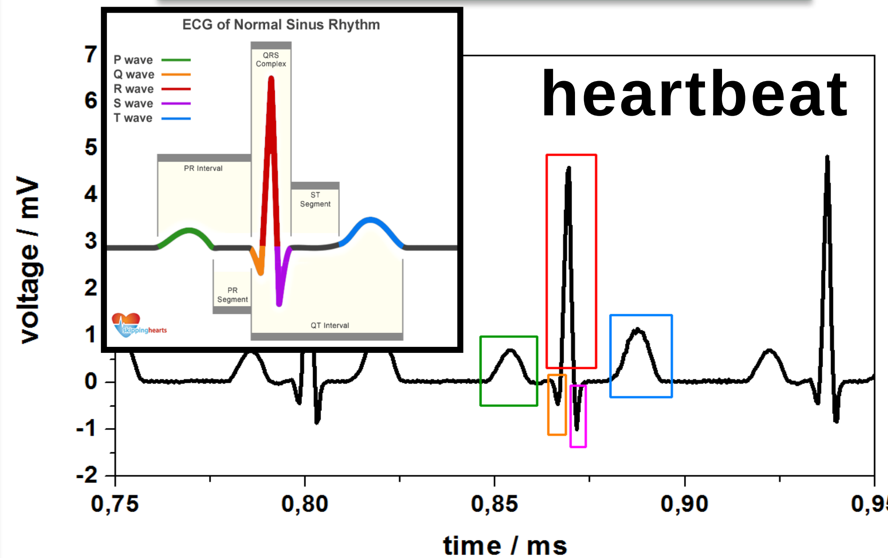
dc waveforms



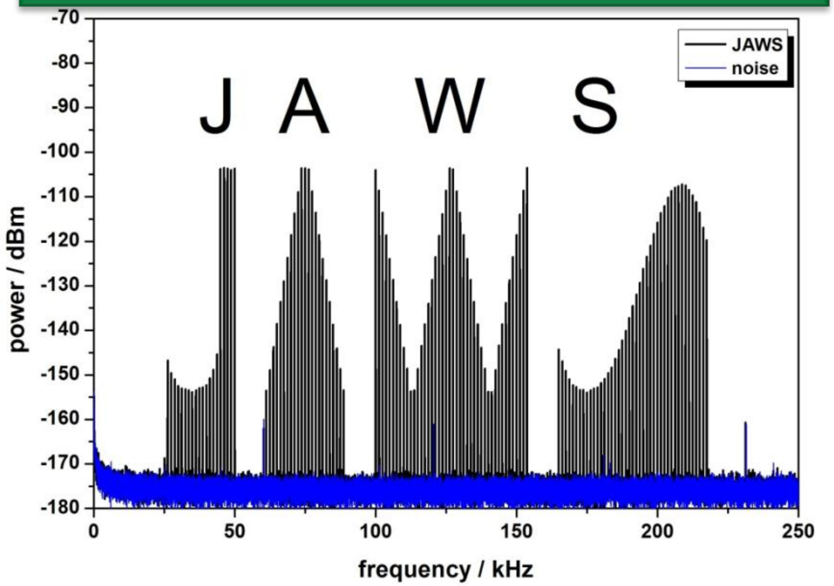
arbitrary waveforms : “all” is possible !

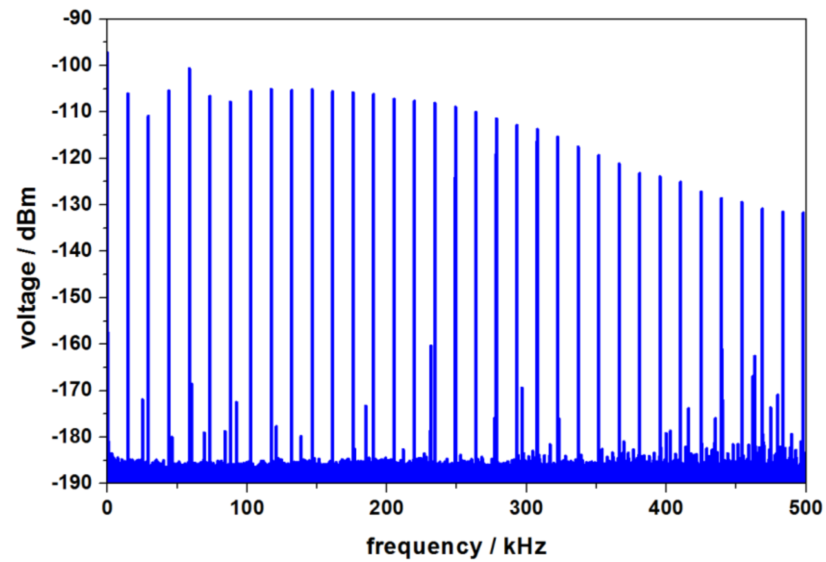


arbitrary time domain

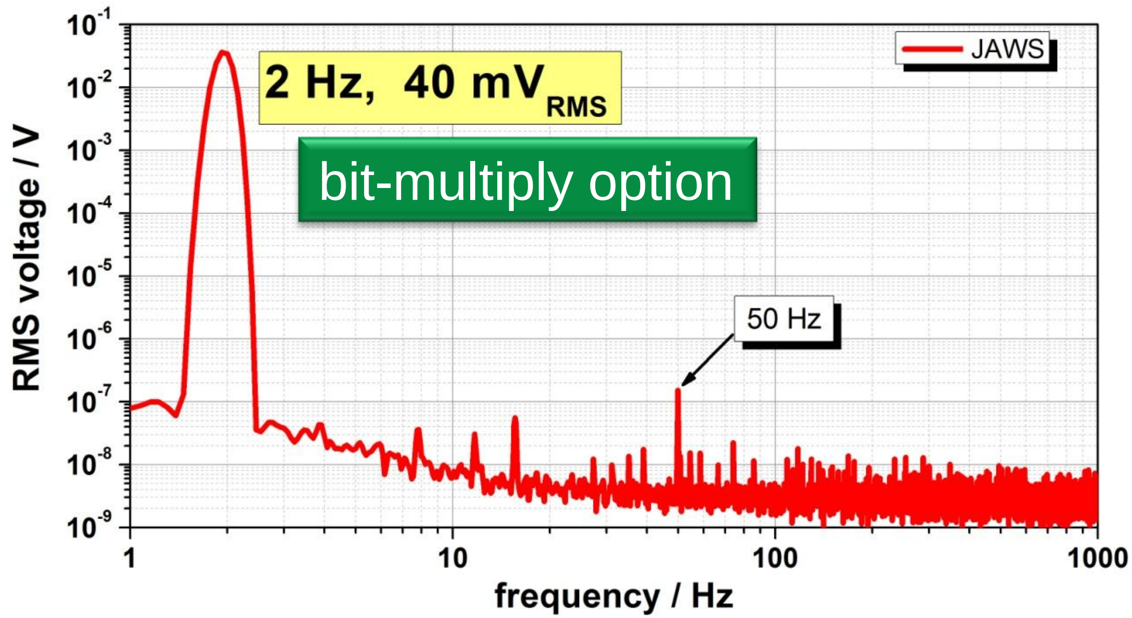


arbitrary frequency domain

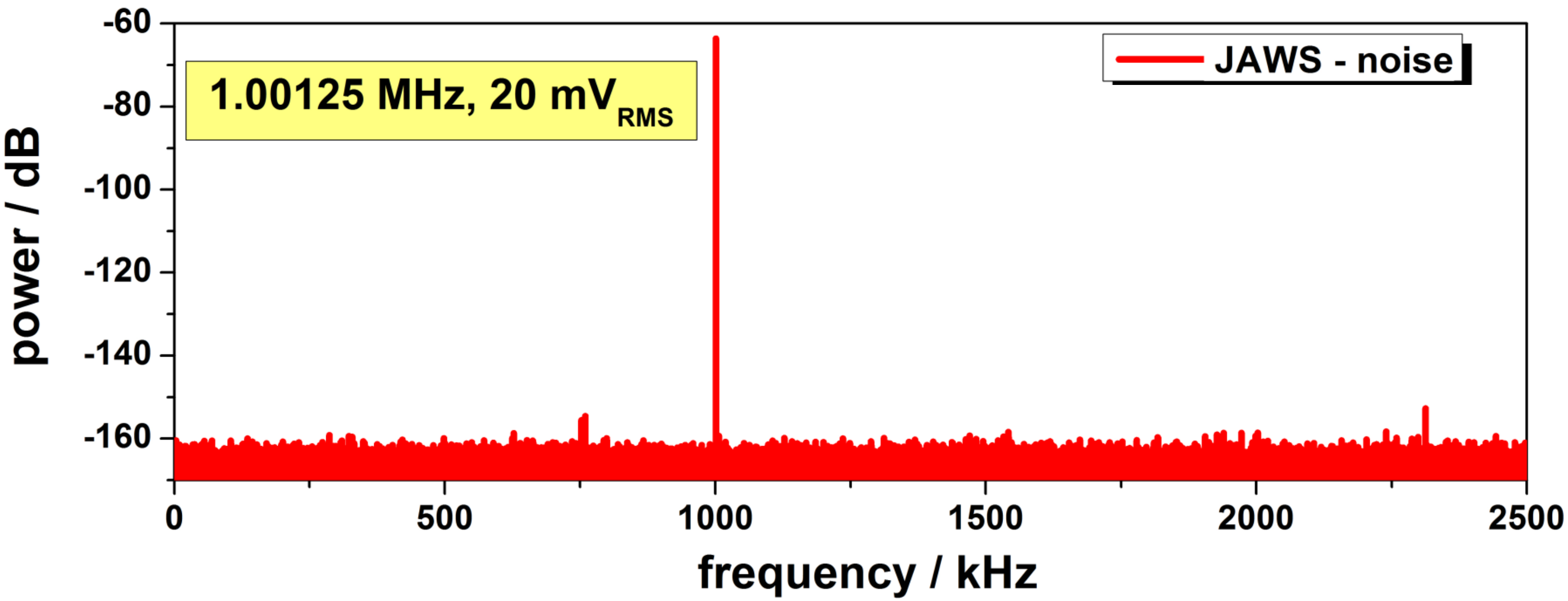




JAWS : large frequency range



frequency range :
DC, 2 Hz … 1 MHz



outline

1. motivation and principle
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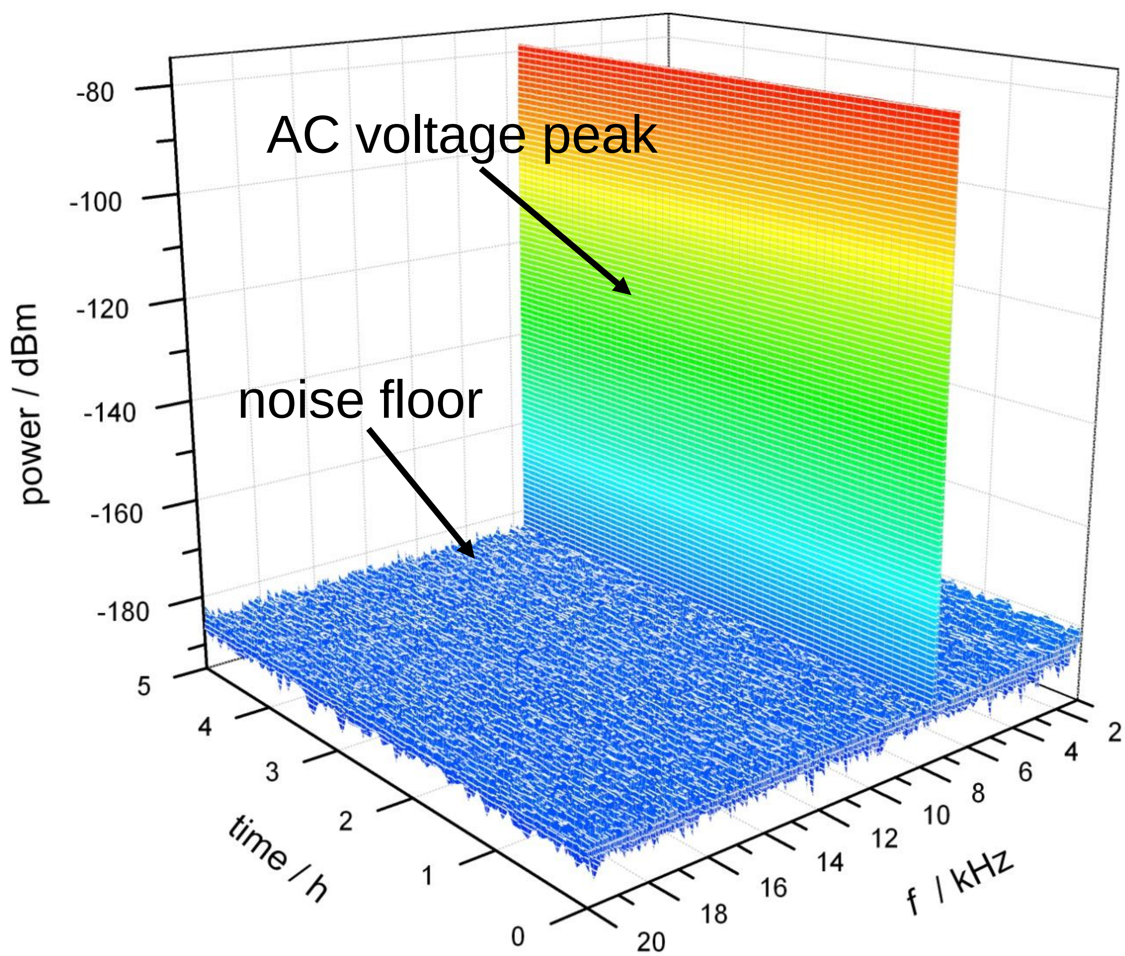
8. summary

JAWS : high time stability (I)

quasi unlimited stabil operation margins !

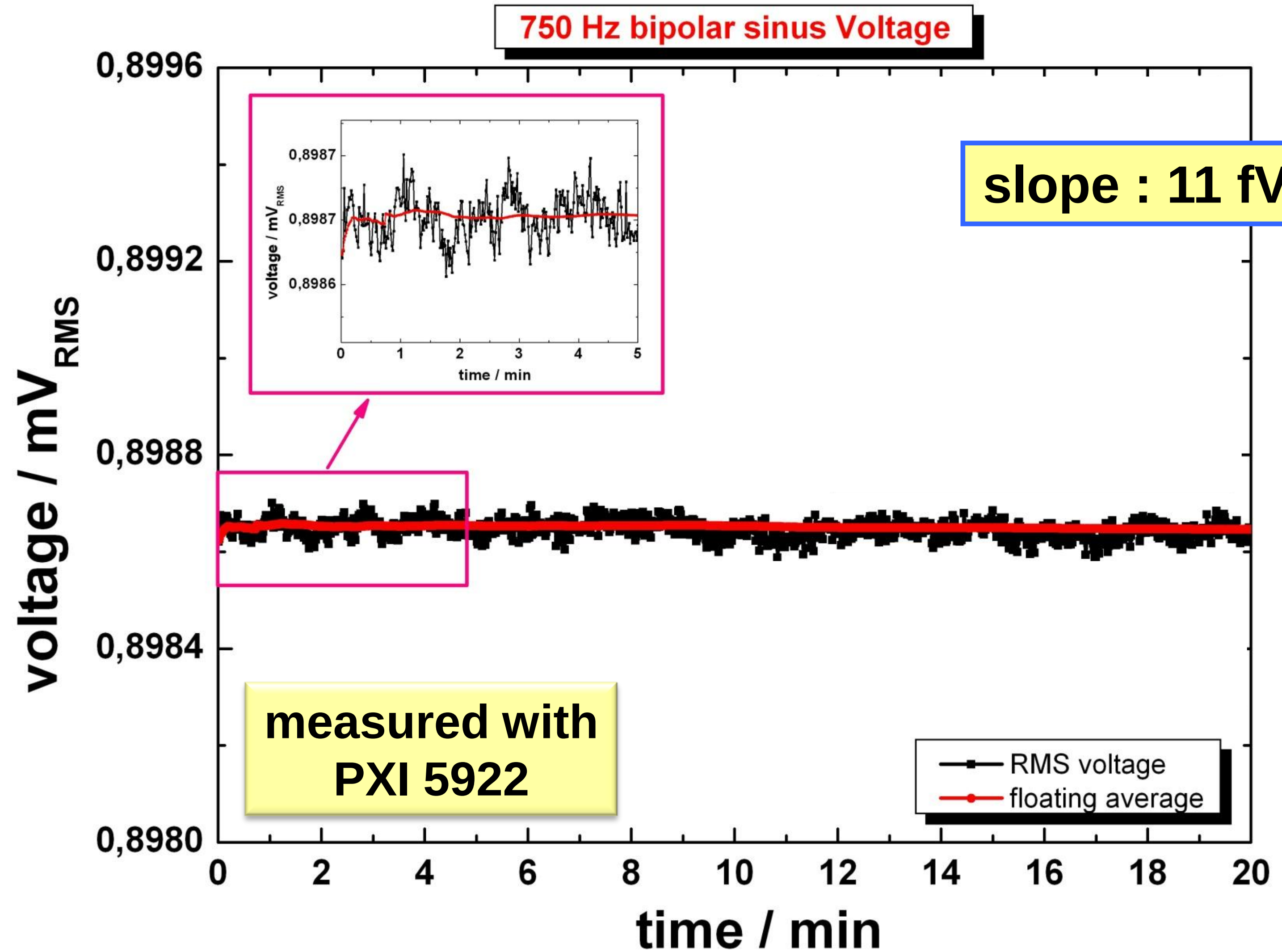
pure spectra for > 5 h without any new adjustments



precondition for any application !

JAWS : high time stability (II)

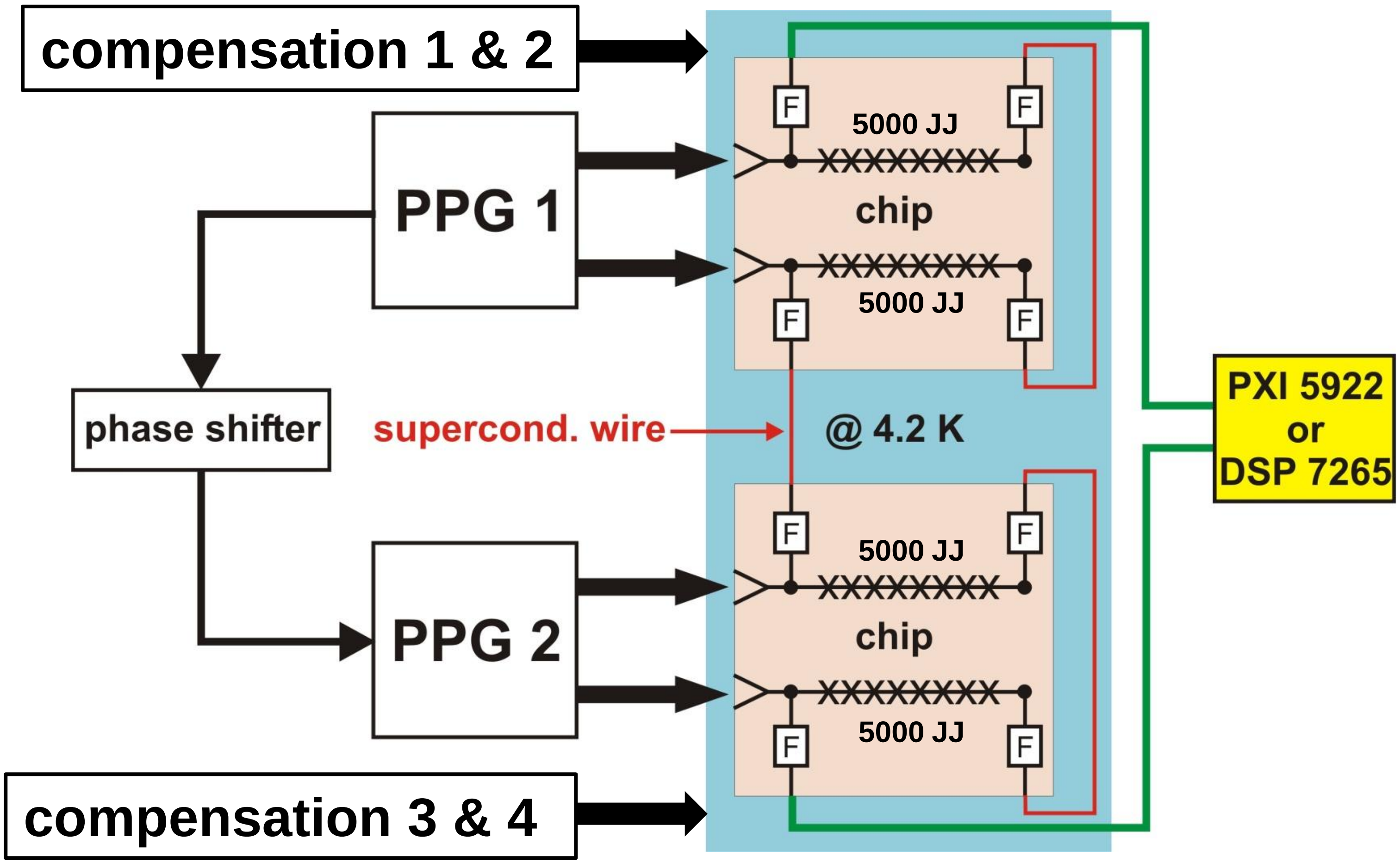
RMS-voltage shows negligible slope vs. time !



slope : 11 fV / 20 min

direct comparison : JAWS vs. JAWS (I)

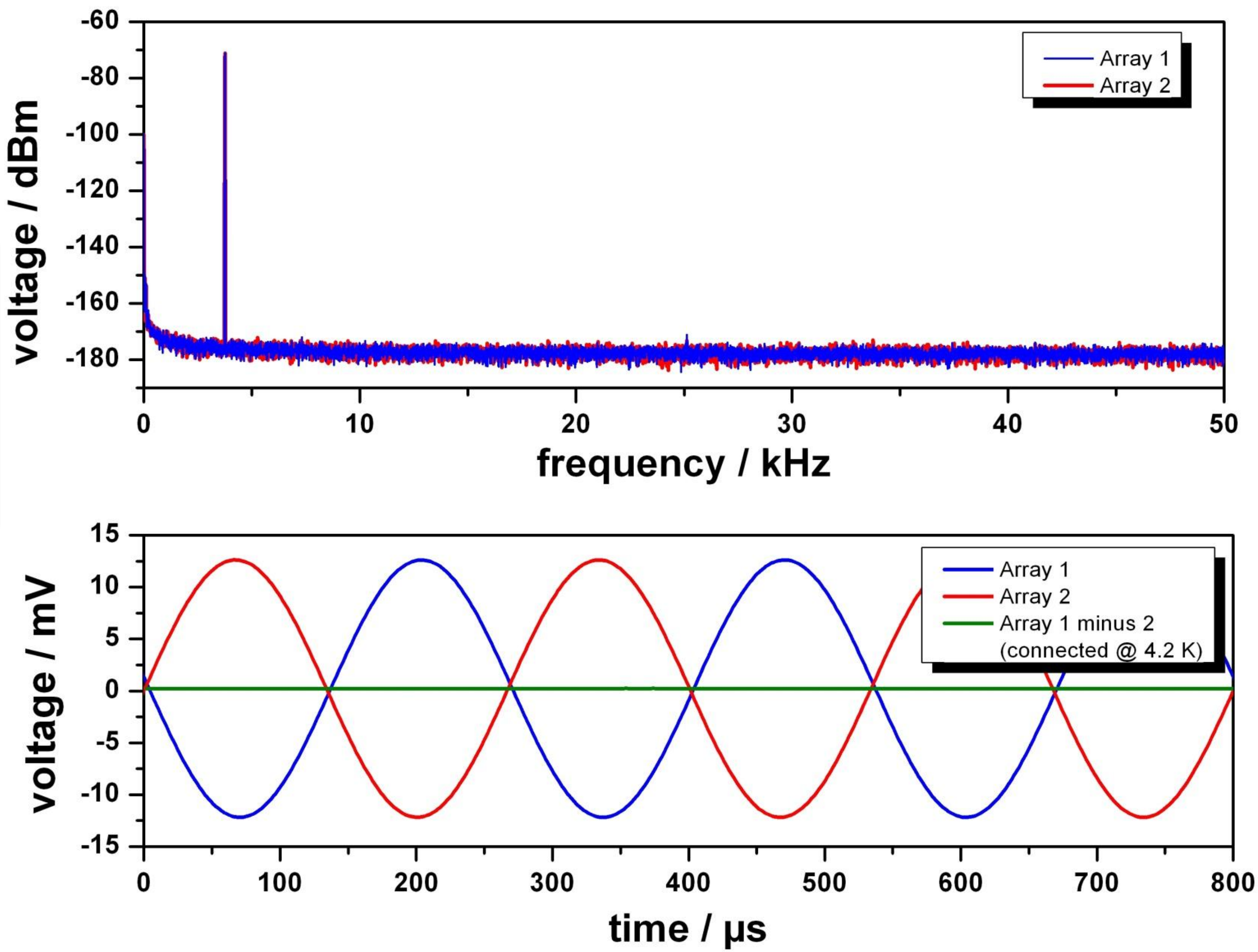
comparison : 10 000 junctions vs. 10 000 junctions



direct comparison : JAWS vs. JAWS (II)

if only one array switched on

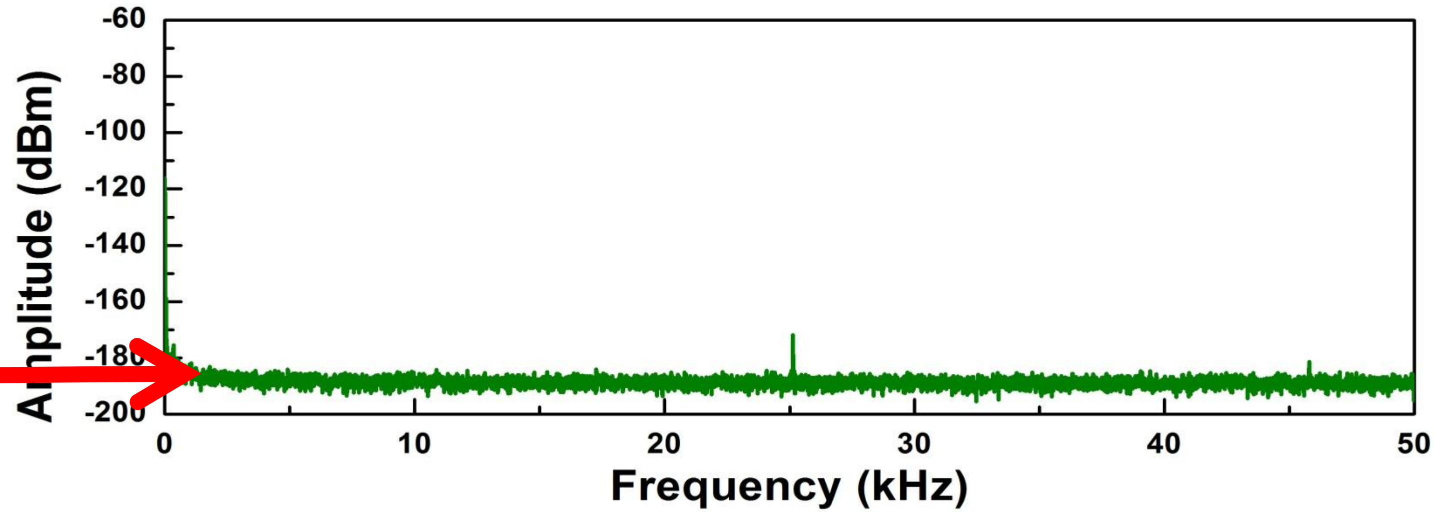
PXI 5922 : voltage difference already only 53 nV_{RMS}

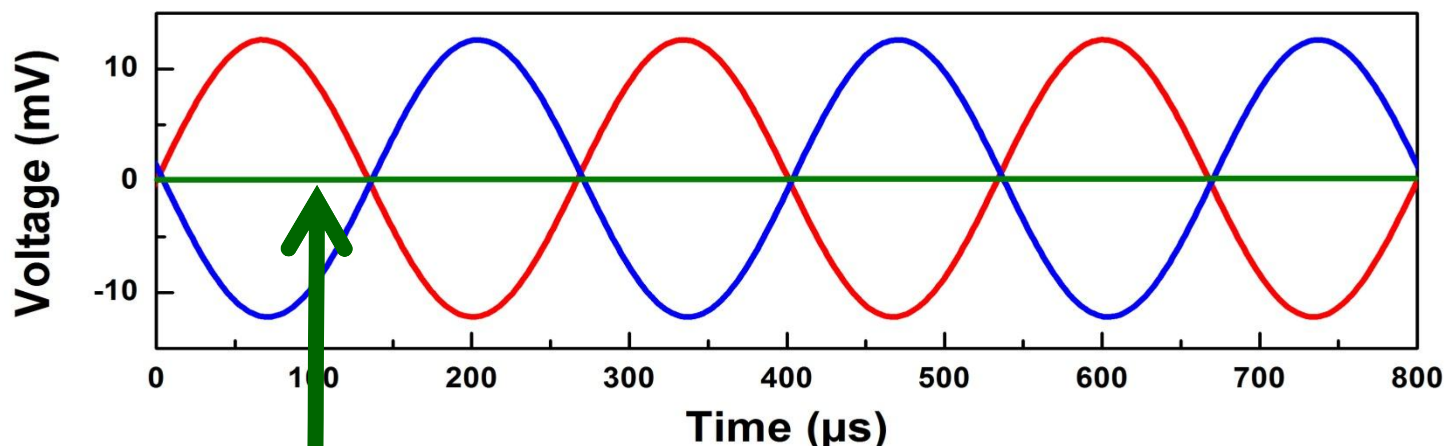


direct comparison : JAWS vs. JAWS (III)

both arrays switched on

PXI 5922 :
voltage difference below noise floor
< 9 nV_{RMS}

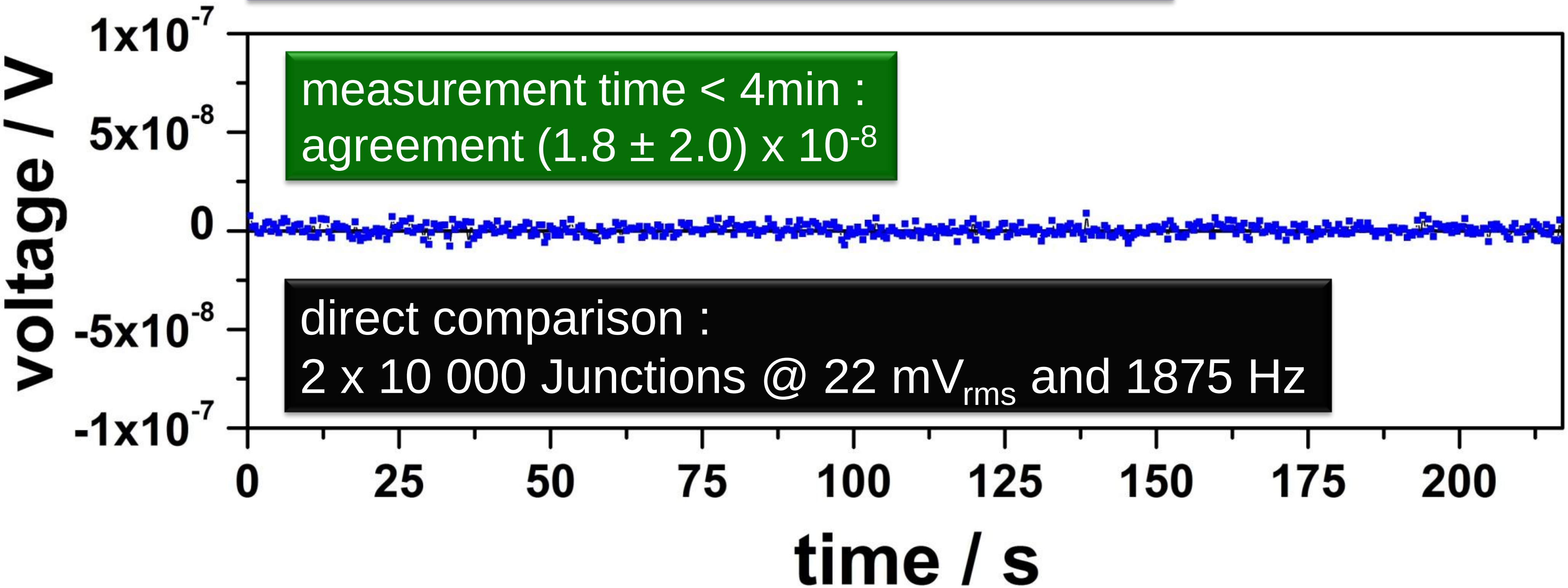




cancellation of waveform, when both arrays are switched on

direct comparison : JAWS vs. JAWS (IV)

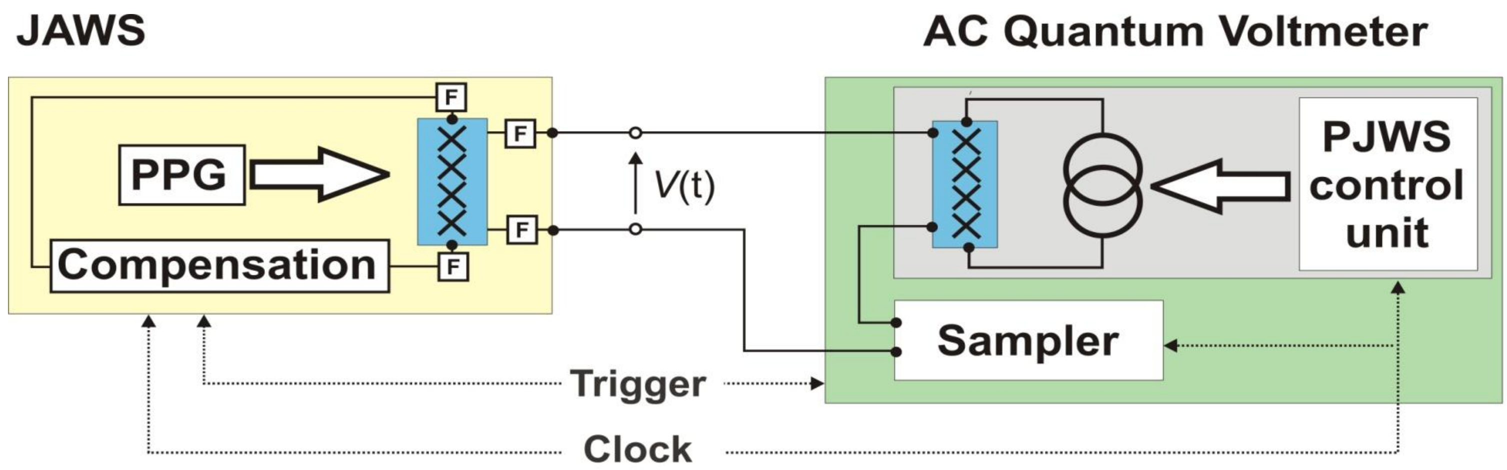
difference voltage (measured with lock-in amp.)



high precision of JAWS !

cf. : Kieler et al., *IEEE Trans. Appl. Supercond.* 23, June 2013

direct comparison : JAWS vs. PJVS (I)



- **problem :**

  no second 1V-JAWS available

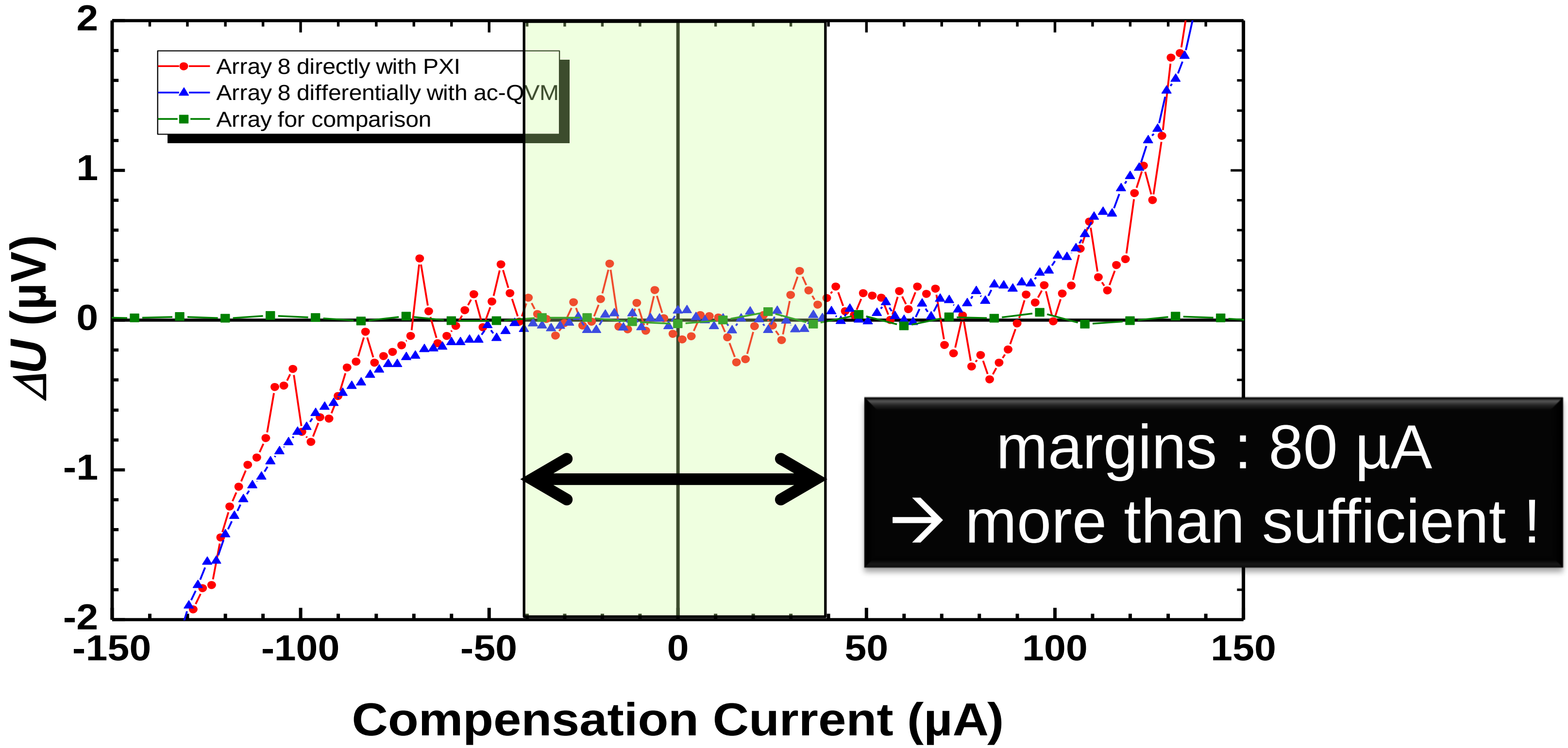
- **solution :**

  PJVS demonstrated : 2 x 10^{-8}

  (J. Lee, CPEM 2014)

direct comparison : JAWS vs. PJVS (II)

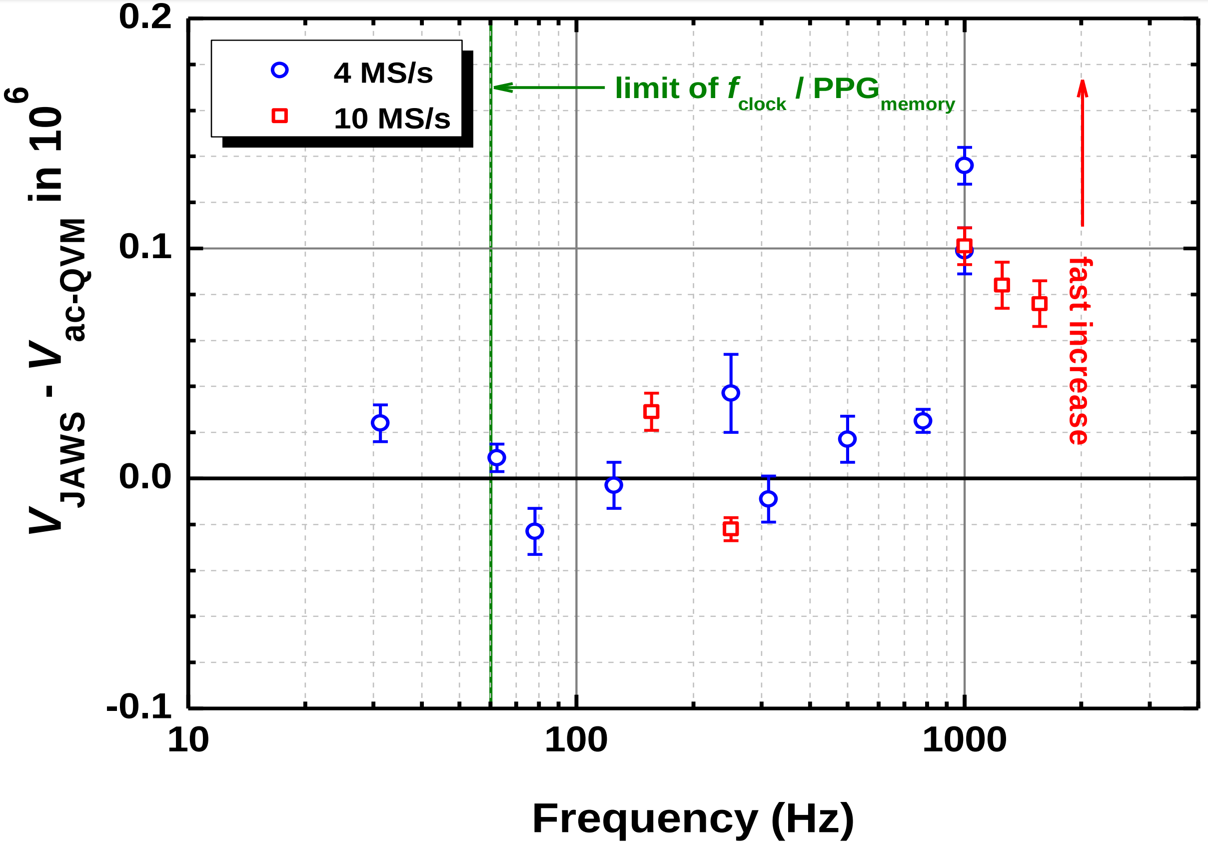
1 array with small but stable operation margins !



- **"weak" array is quantized**
- **all other arrays with bigger margins**
- **measurement resolution : PJVS > PXI5922**

direct comparison : JAWS vs. PJVS (III)

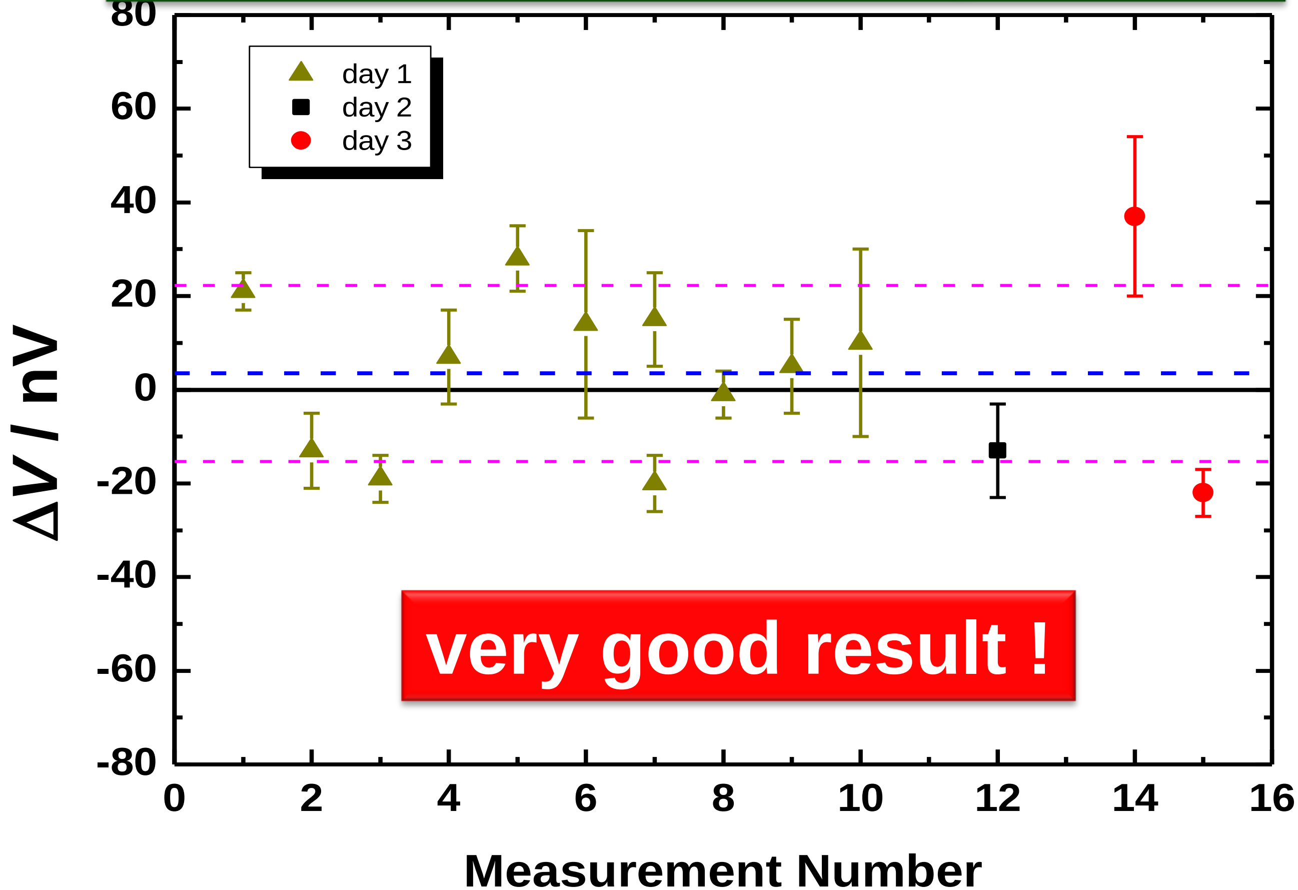
deviation JAWS-PJVS vs. frequency



- new PPG : *f* < 60 Hz possible
- good results : *f* < 1 kHz !
- to investigate : *f* > 1 kHz

direct comparison : JAWS vs. PJVS (IV)

deviation JAWS-PJVS @ 250 Hz



very good result !

$$V_{\text{JAWS}} - V_{\text{ac-QVM}} = +3.5\ \text{nV} \pm 12\ \text{nV}$$

cf. : Behr et al., *Metrologia* 2015

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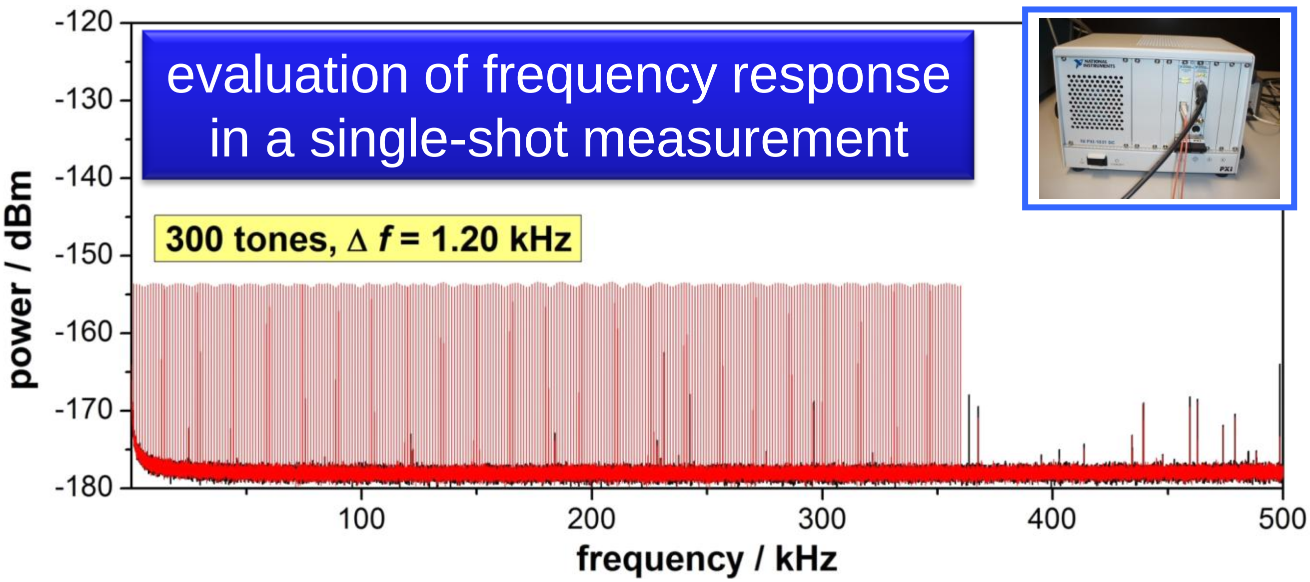
JAWS : first "applications"

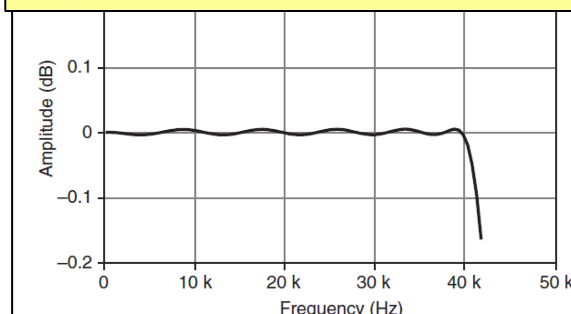
- characterization of fast **analog-digital-converter** NI-PXI 5922 ✓
- AC-DC **thermo-converter** Fluke 792A ✓
- characterization of NPL **broadband-amplifier** ✓

PXI 5922 :

evaluation of frequency response in a single-shot measurement



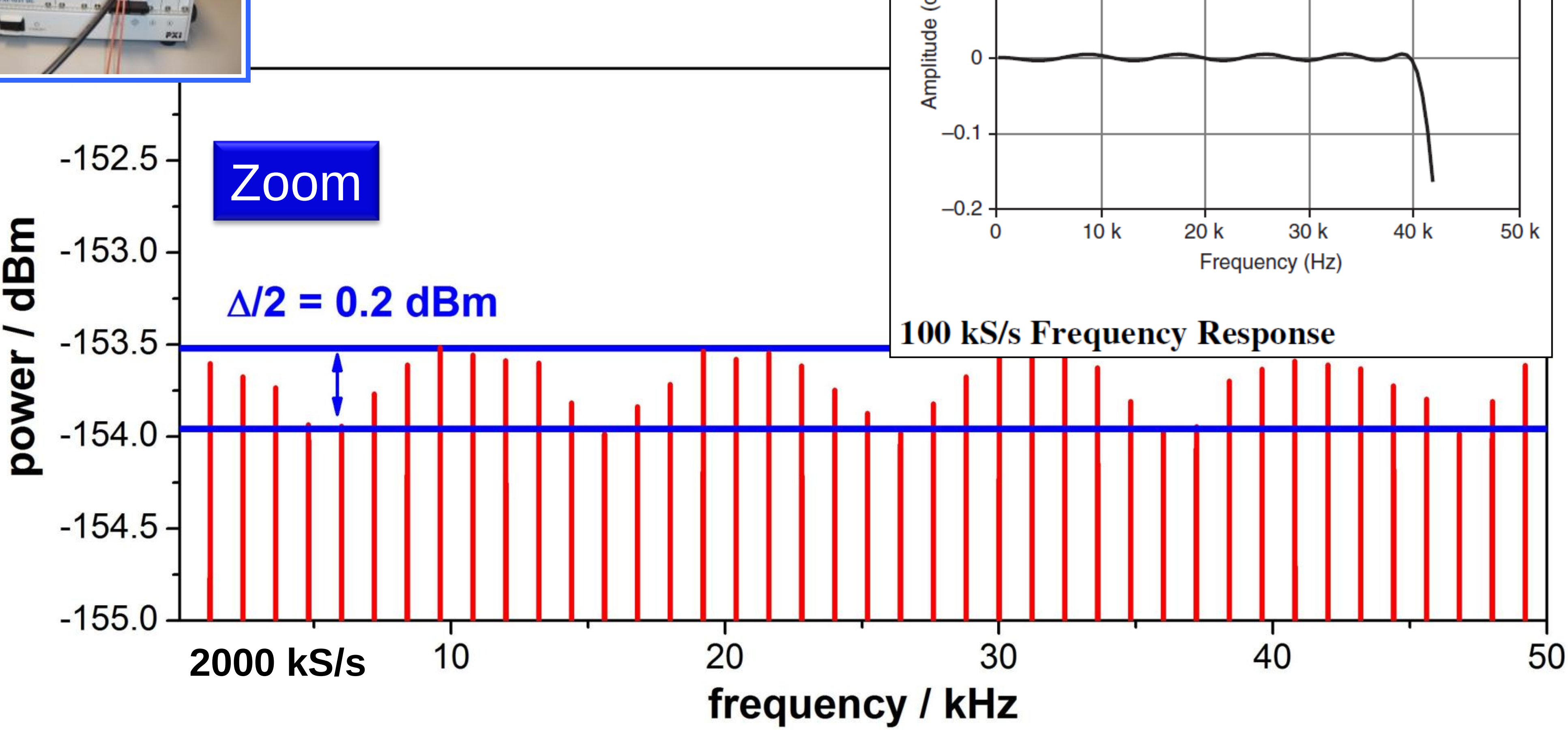
spezification : PXI 5922



100 kS/s Frequency Response

characterization NI-PXI 5922

from specification : PXI 5922

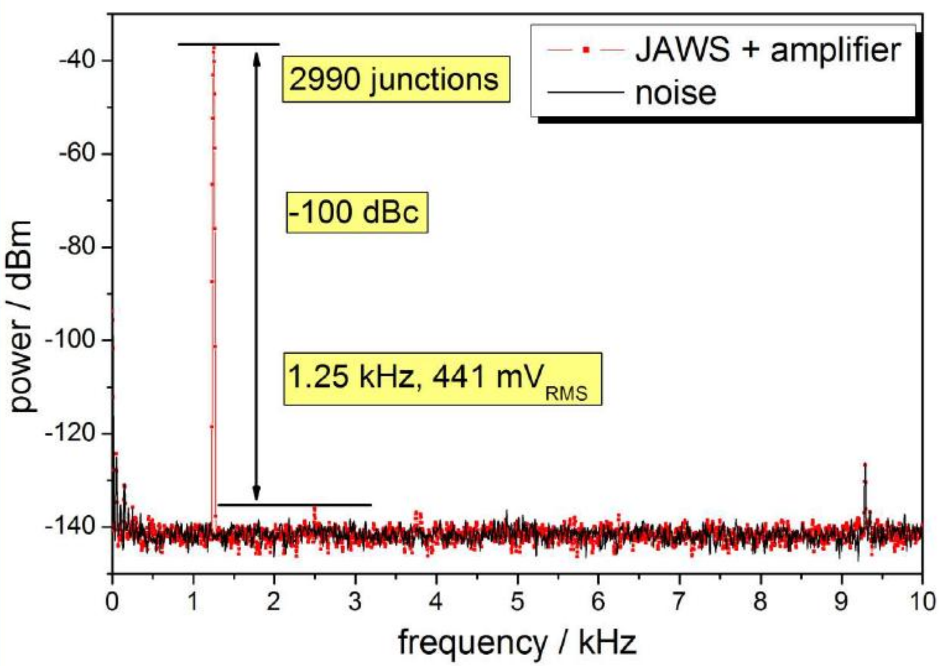


JAWS : 300-tone waveform

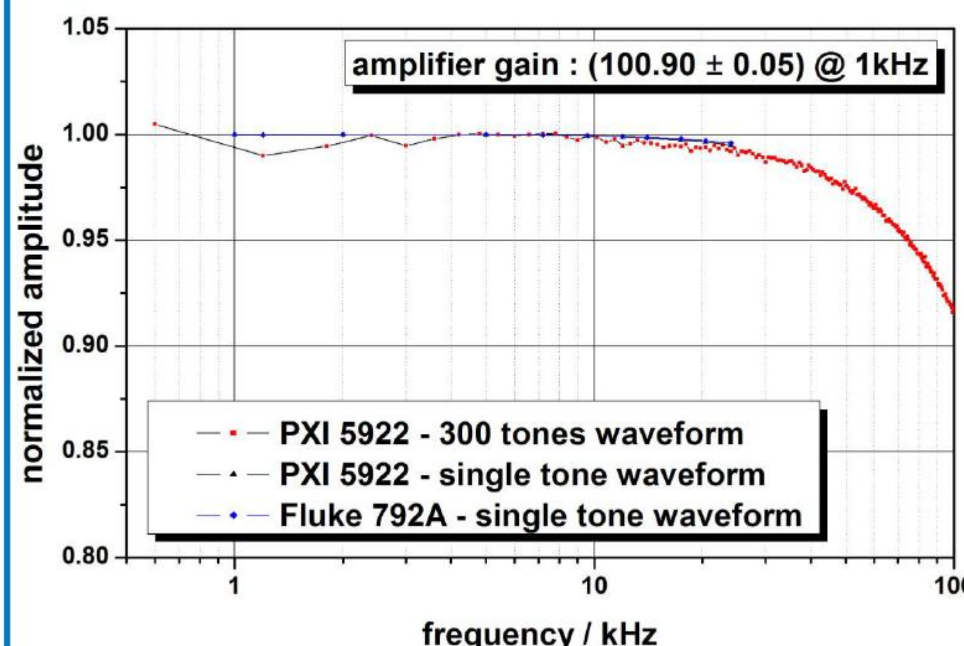
characterization NPL-amplifier

gain and frequency response

a) waveform with amplifier : 441 mV_{RMS}



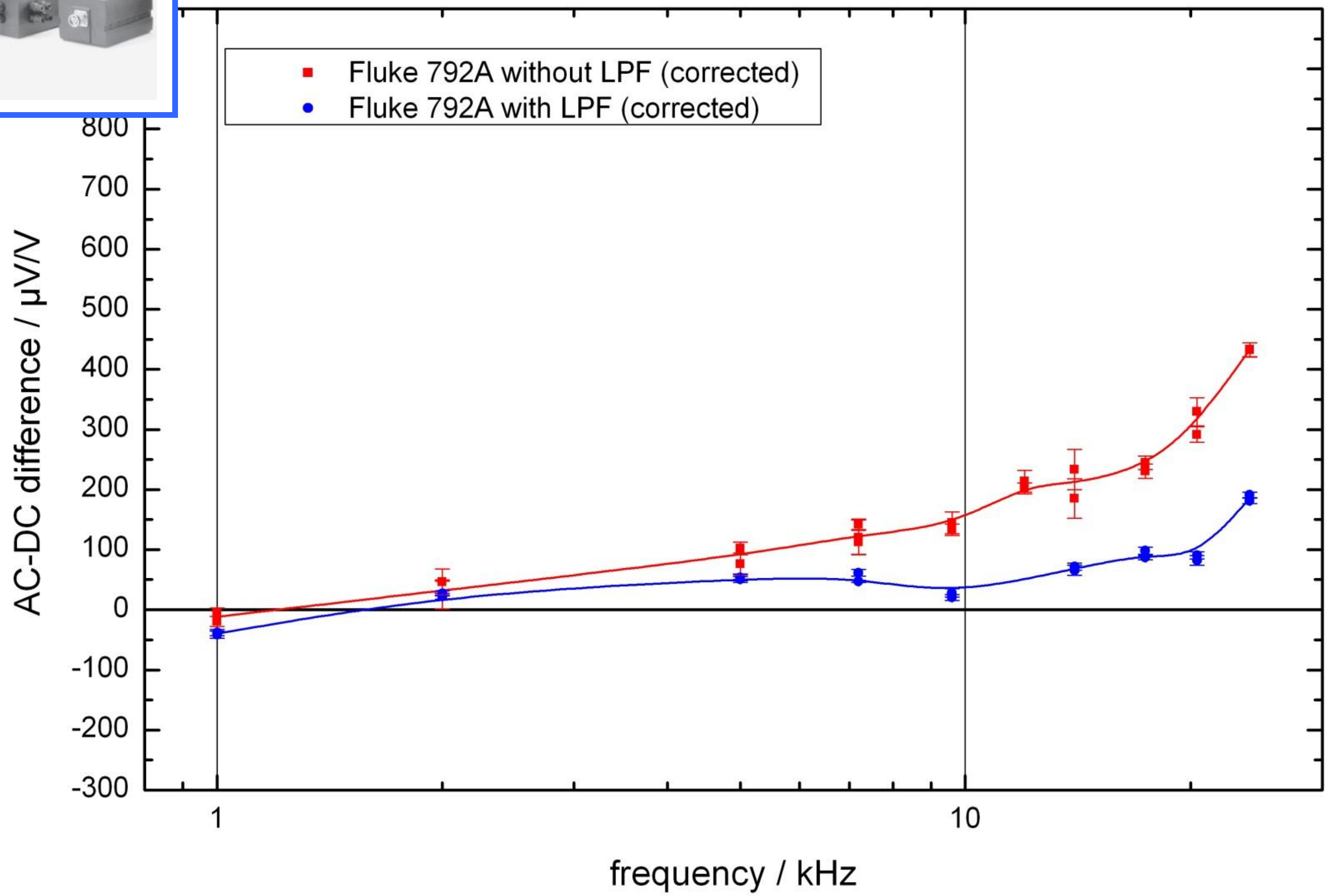
b) gain and bandwidth of amplifier :



JAWS : sine and 300-tone waveforms

thermo-converter : Fluke 792A

ac-dc difference vs. frequency



JAWS : sine waveform

PJVS + JAWS : principle (I)

AC-Programmable Josephson Voltage Standard

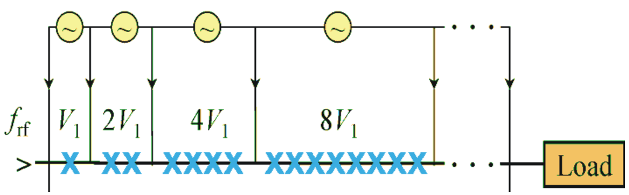
Josephson Arbitrary Waveform Synthesizer

70 GHz

$$V_{AC}(t) = M \cdot N \cdot \Phi_0 \cdot f$$

15 GHz

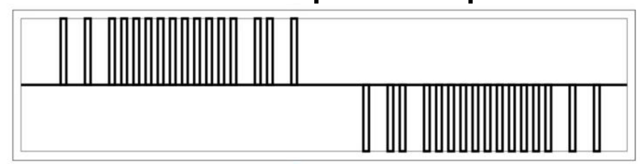
binary



$M(t)$

$f_p(t)$

pulse operation



number Josephson junctions

pulse repetition frequency

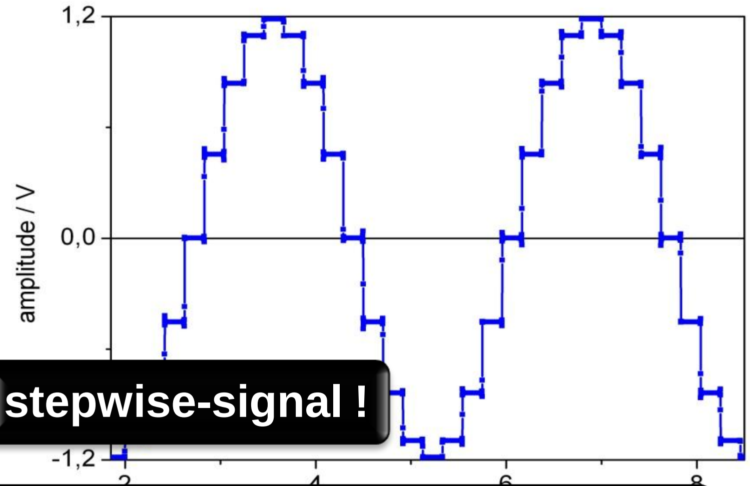
- **+ 1V and 10V**
- **- transients limit accuracy**
- **- spectra contain many harmonics**

- **+ pure spectra**
- **+ high accuracy**

PJVS + JAWS : high output voltage and pure spectra ?!

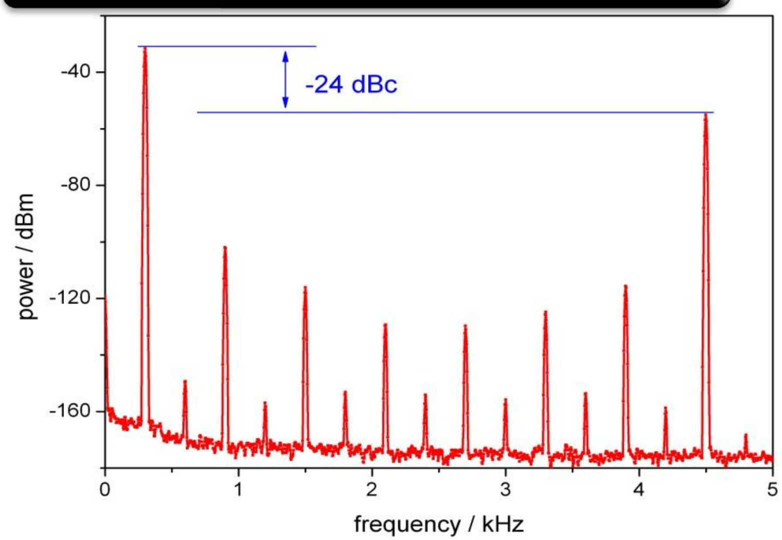
PJVS + JAWS : principle (II)

AC-Programmable Josephson Voltage Standard

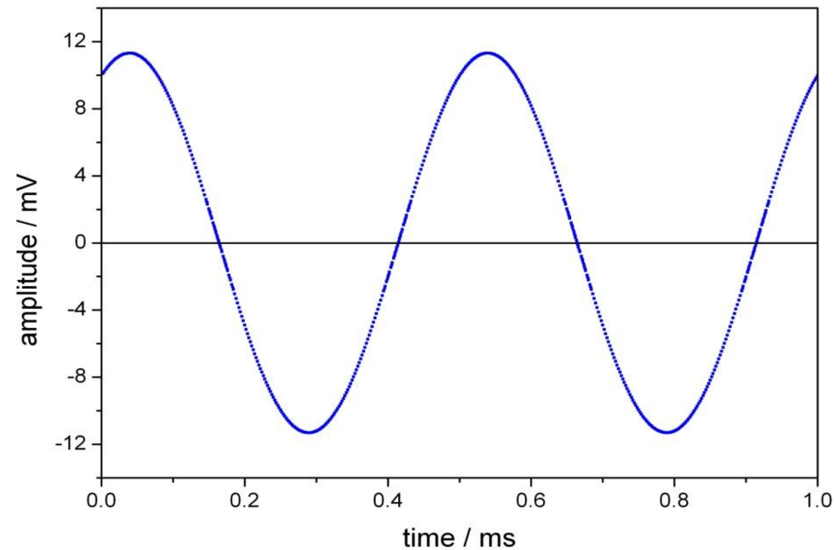


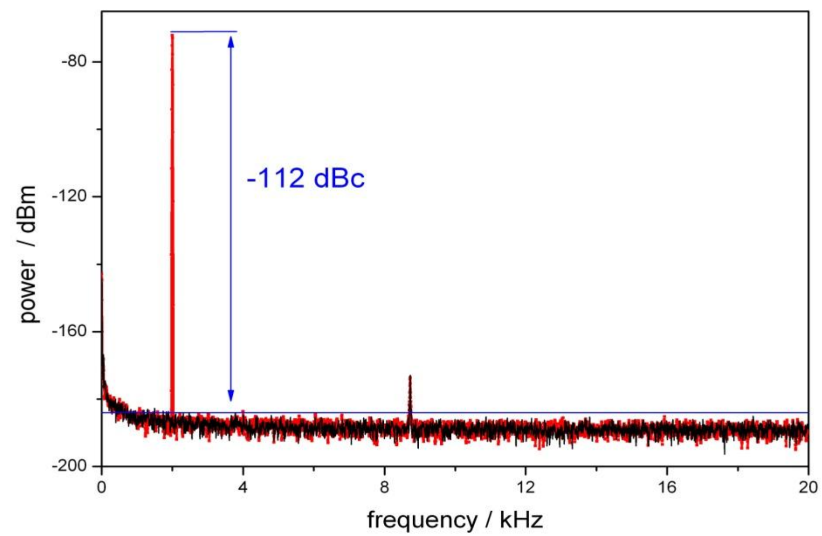
stepwise-signal !

non quantized between steps !



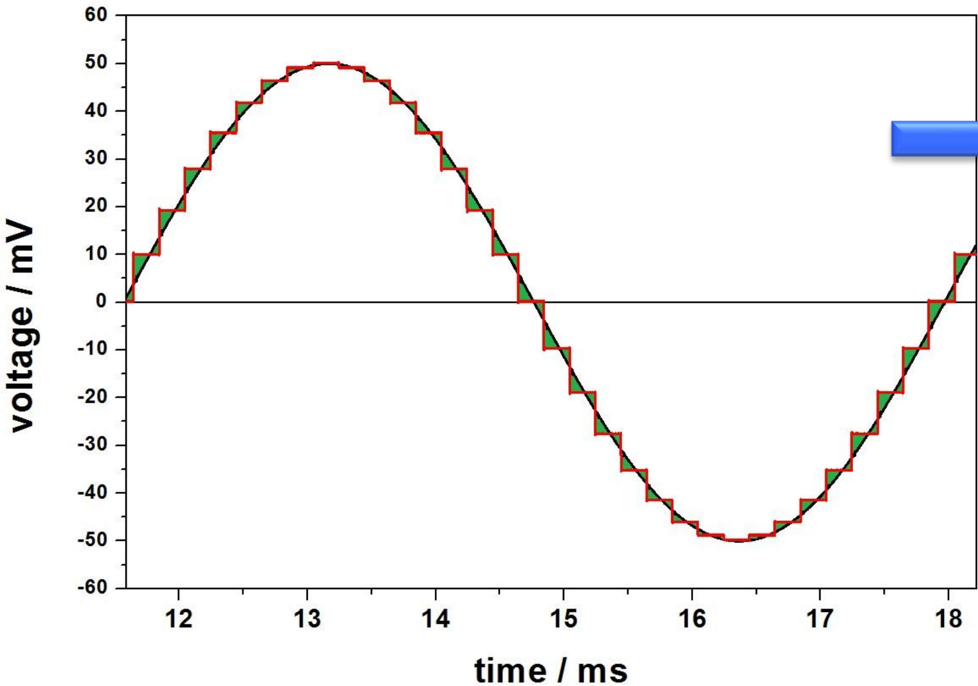
Josephson Arbitrary Waveform Synthesizer

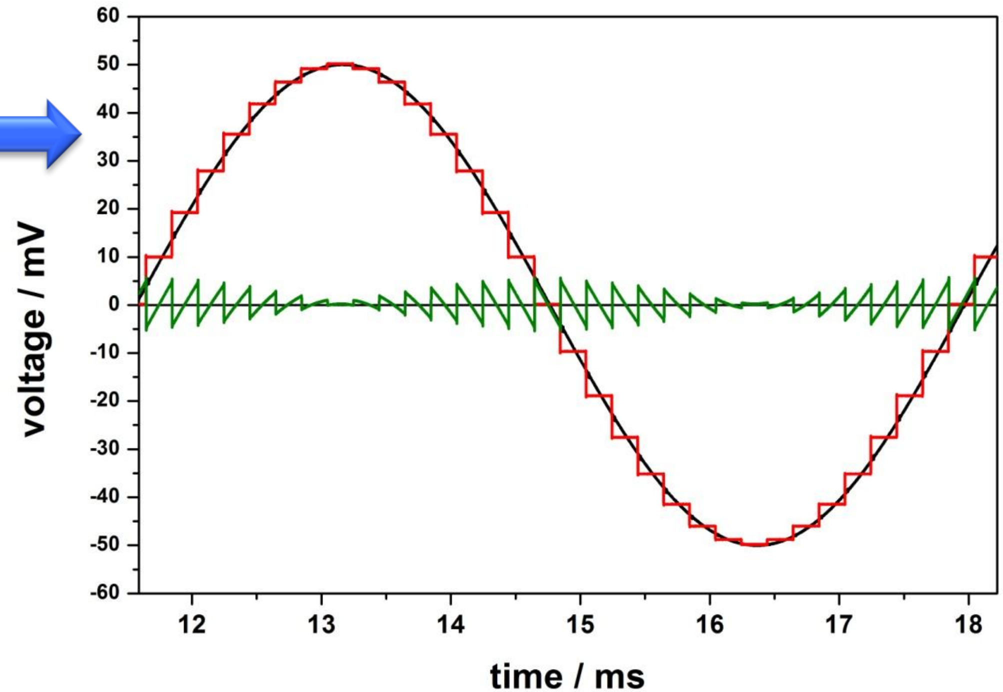




PJVS + JAWS : principle (III)

JAWS „completes“ PJVS to SINUS **PJVS+JAWS = SINUS**

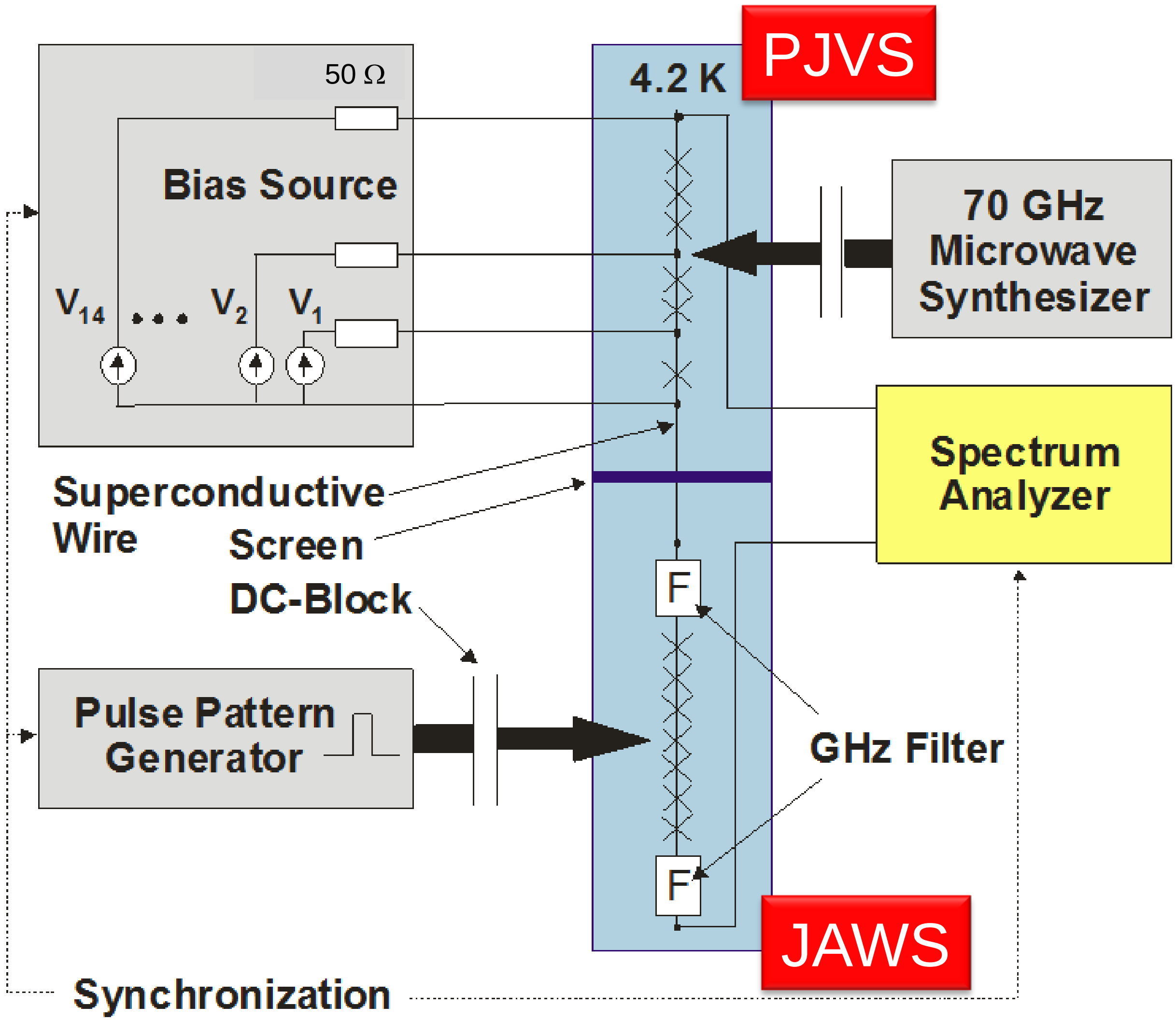




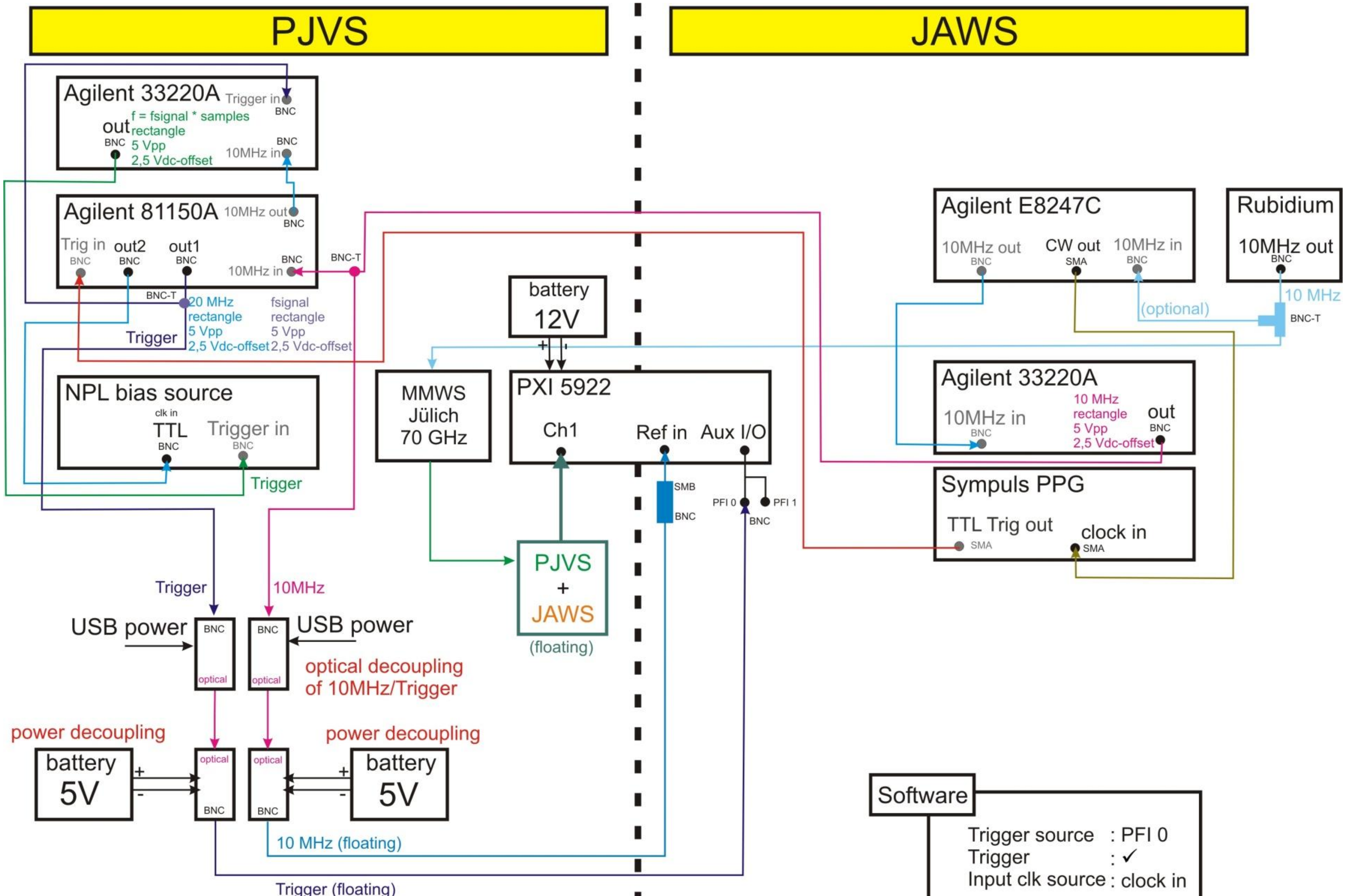
combination : large voltage PJVS and pure spectrum JAWS !

idea : PTB-patent, Kahmann et al., 2006

PJVS + JAWS : setup (I)



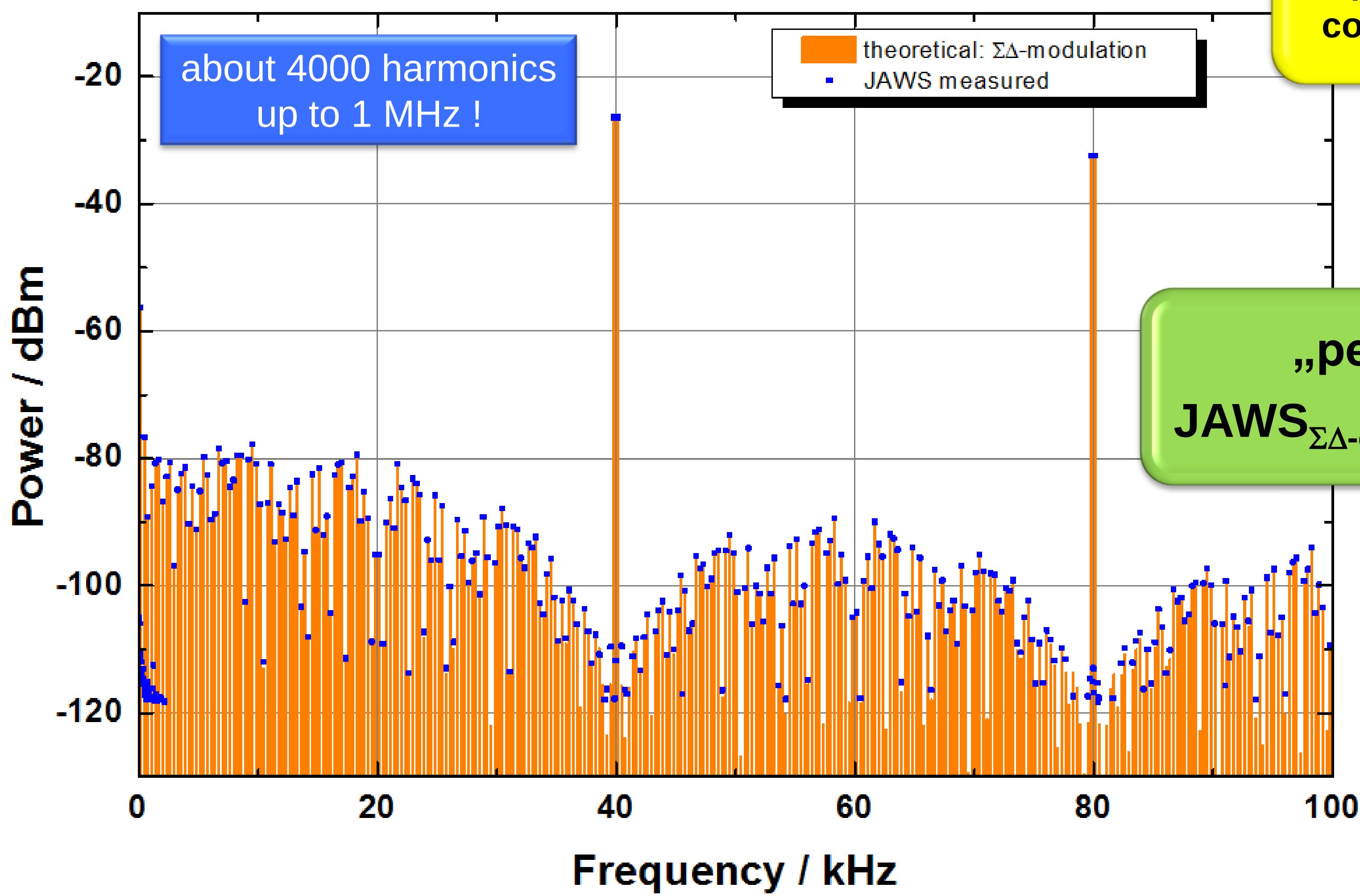
PJVS + JAWS : setup (II)



Kieler, 10.2013

FFT ΣΔ-code $\stackrel{!}{=}$ JAWS-measurement !

156.25 Hz sine wave with 256 samples (PJVS)



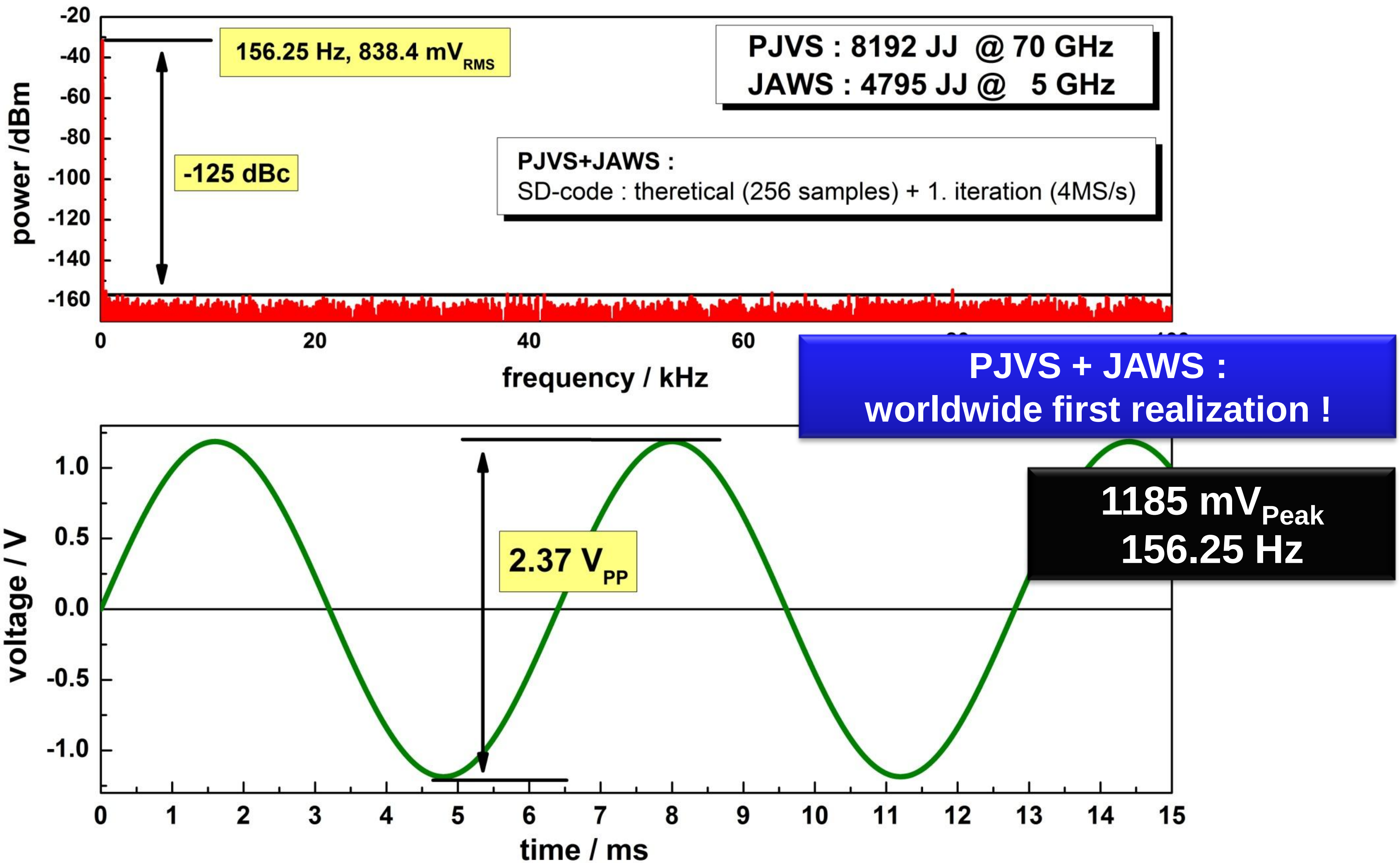
JAWS :

has to "compensate" complex PJVS spectrum

„perfect" match

$JAWS_{\Sigma\Delta\text{-code}}$ and $JAWS_{meas.}$

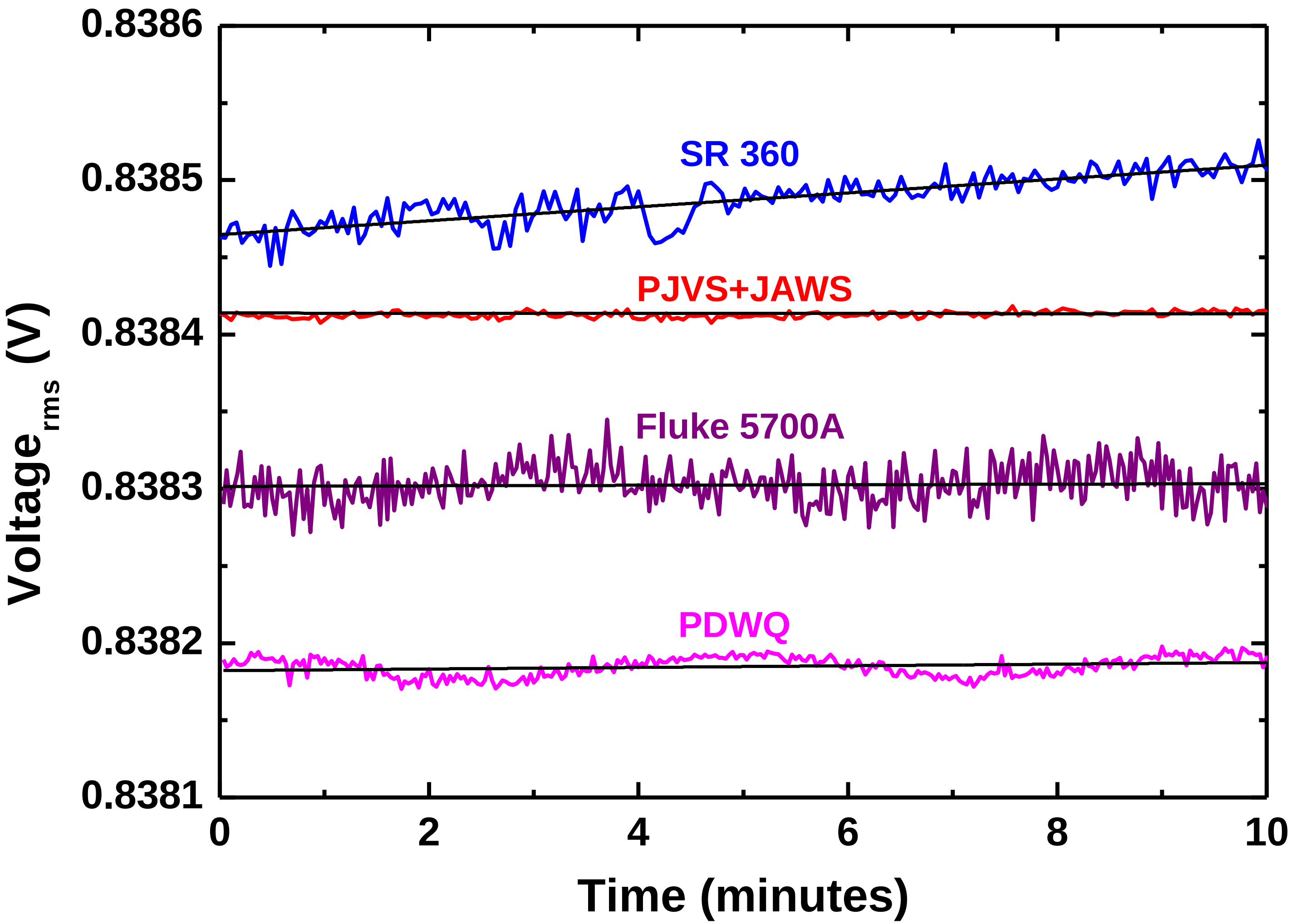
PJVS + JAWS : pure spectrum



Behr et al., IEEE TRANS. INSTR. MEAS., 62(6), 2013

PJVS + JAWS : quantum stability

low noise and low drift compared to
„best“ semiconductor-based synthesizers !



outline

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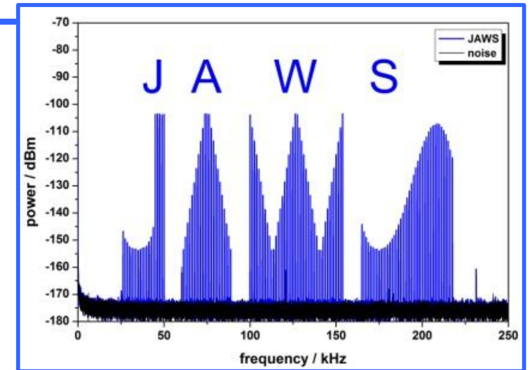
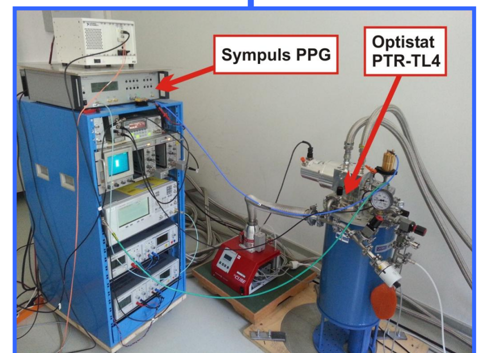
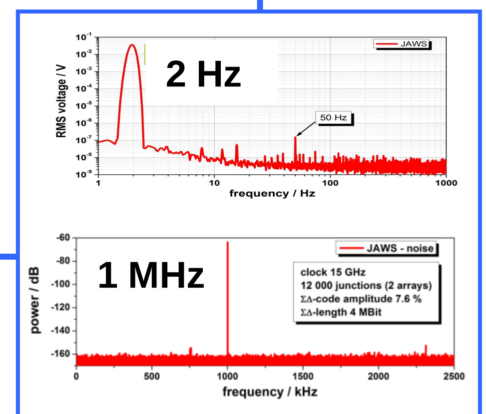
Summary (I)

high-quality AC-waveforms

- Nb_xSi_{1-x}- arrays with **triple-stacked** junctions
- up to **8 arrays** in series : **63 000 junctions**
- output voltage up to **1 V_{RMS} (2.83 V_{PP})**
- high spectral purity : SNR better than **-120 dBc**
- high frequency range : **DC, 2 Hz … 1 MHz**
- **arbitrary** waveforms demonstrated
- JAWS successfully operated in **cryocooler**



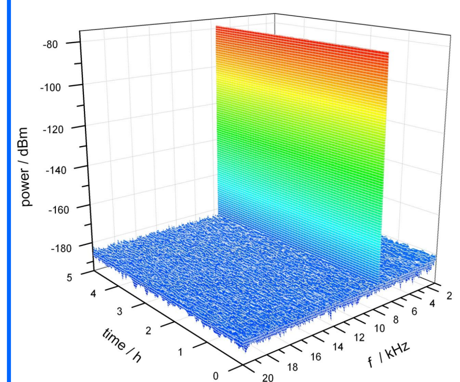


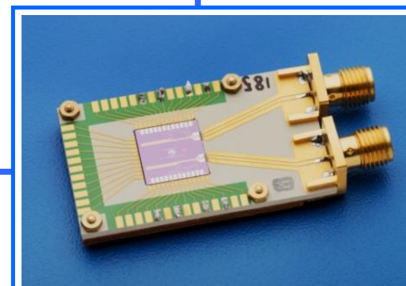


Summary (II)

high-quality AC-waveforms

- **3 JAWS systems operational :**
  - **JAWS 1 : 1 V_{RMS}**
  - **JAWS 2 : 2 x 100 mV_{RMS}**
  - **JAWS 3 : PJVS + JAWS : 1.18 V with SNR -125 dBc**
- **high time stability : low noise and no drift**
- **first applications : e.g. characterization of HF devices**
- **direct comparison JAWS - JAWS : (1.8 ± 2.0) x 10^{-8} @ 3750 Hz**
- **direct comparison JAWS - PJVS : (3.5 ± 11.7) x 10^{-9} @ 250 Hz**





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Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

AC Metrology with Josephson Voltage Standards

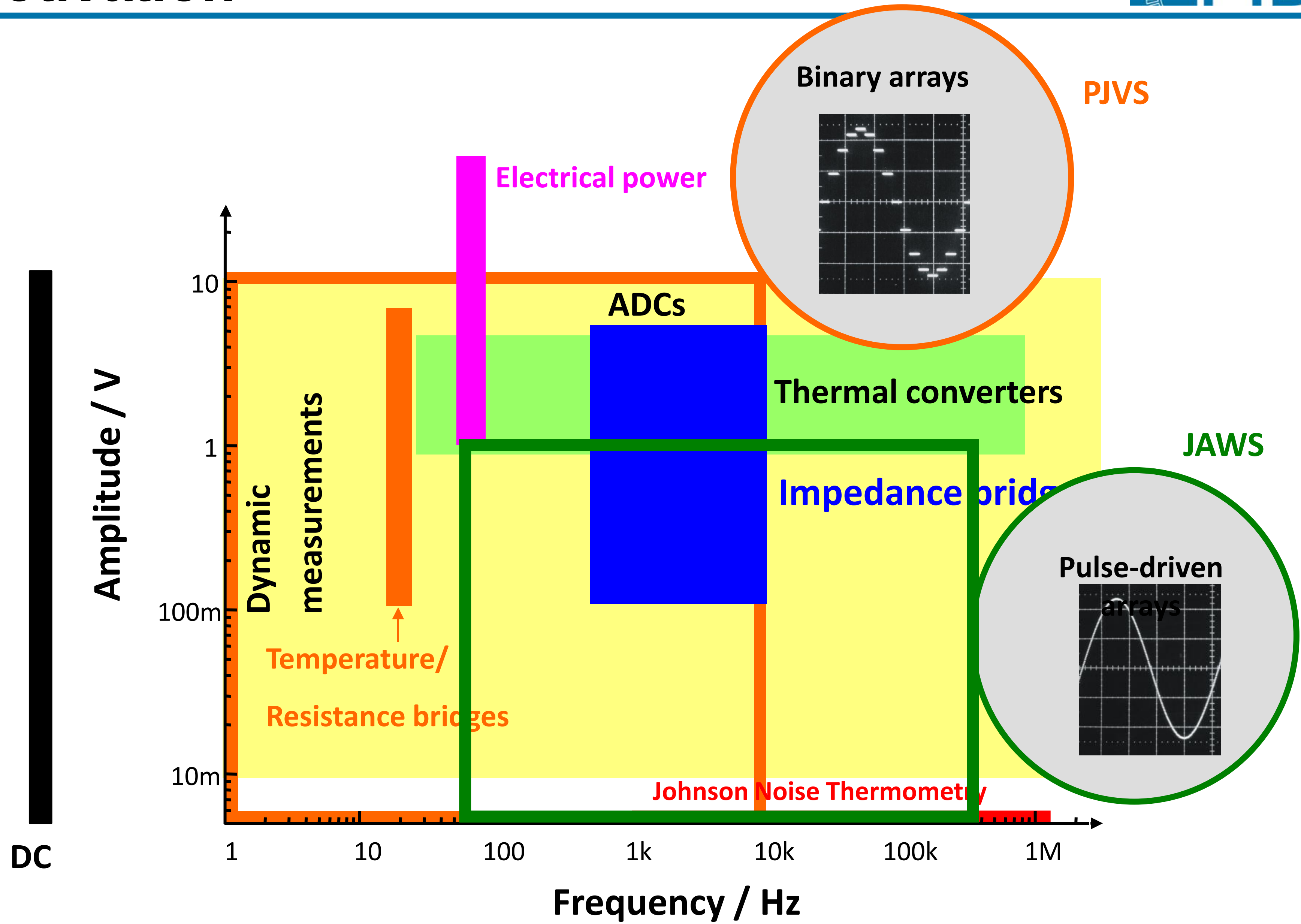
Dc Applications & Power standards

Luis Palafox

Outline

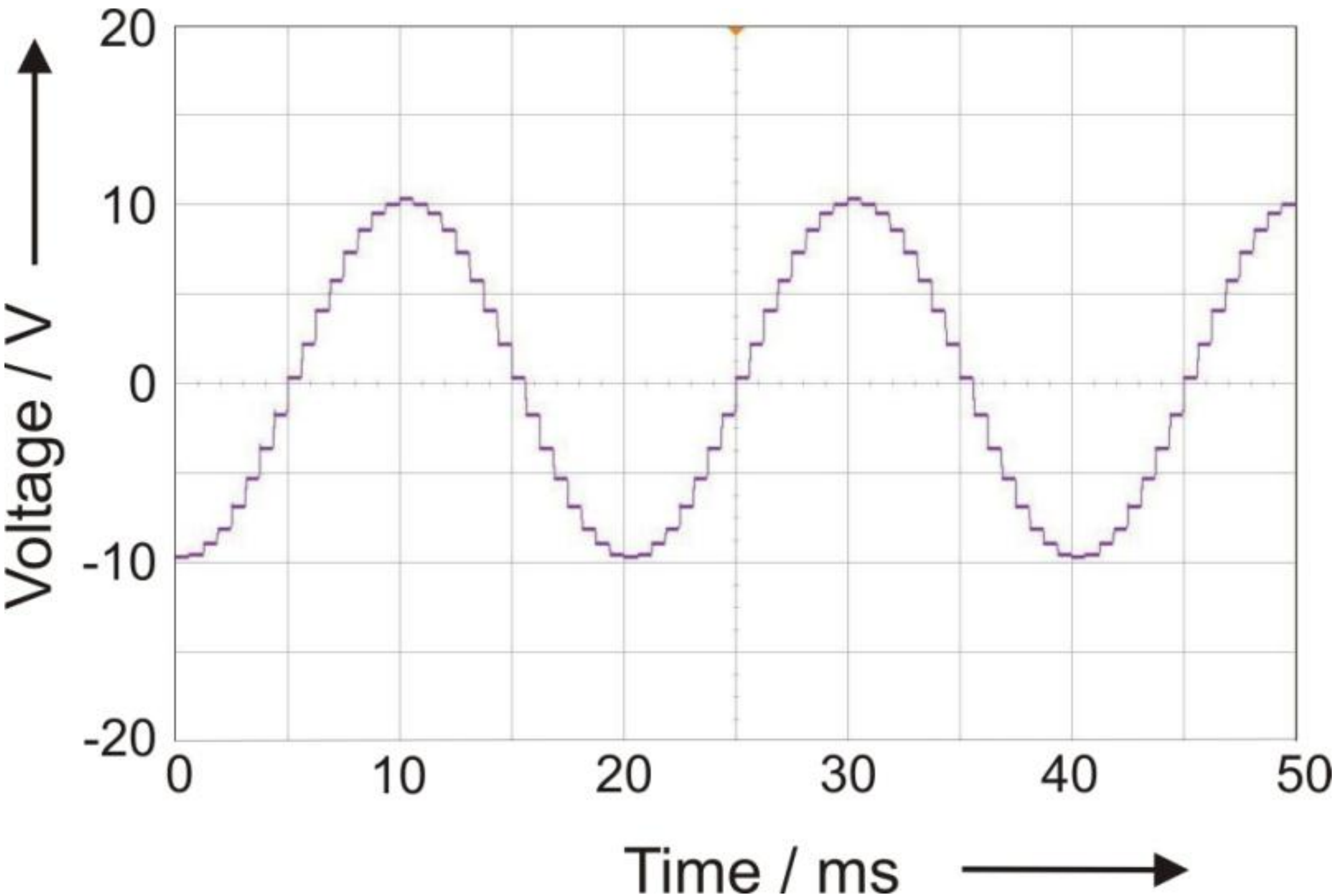
- Introduction
- Verification of quantisation
- DC Applications
- AC characterization of ADCs
- Power standard at PTB
- Other power standards

Motivation

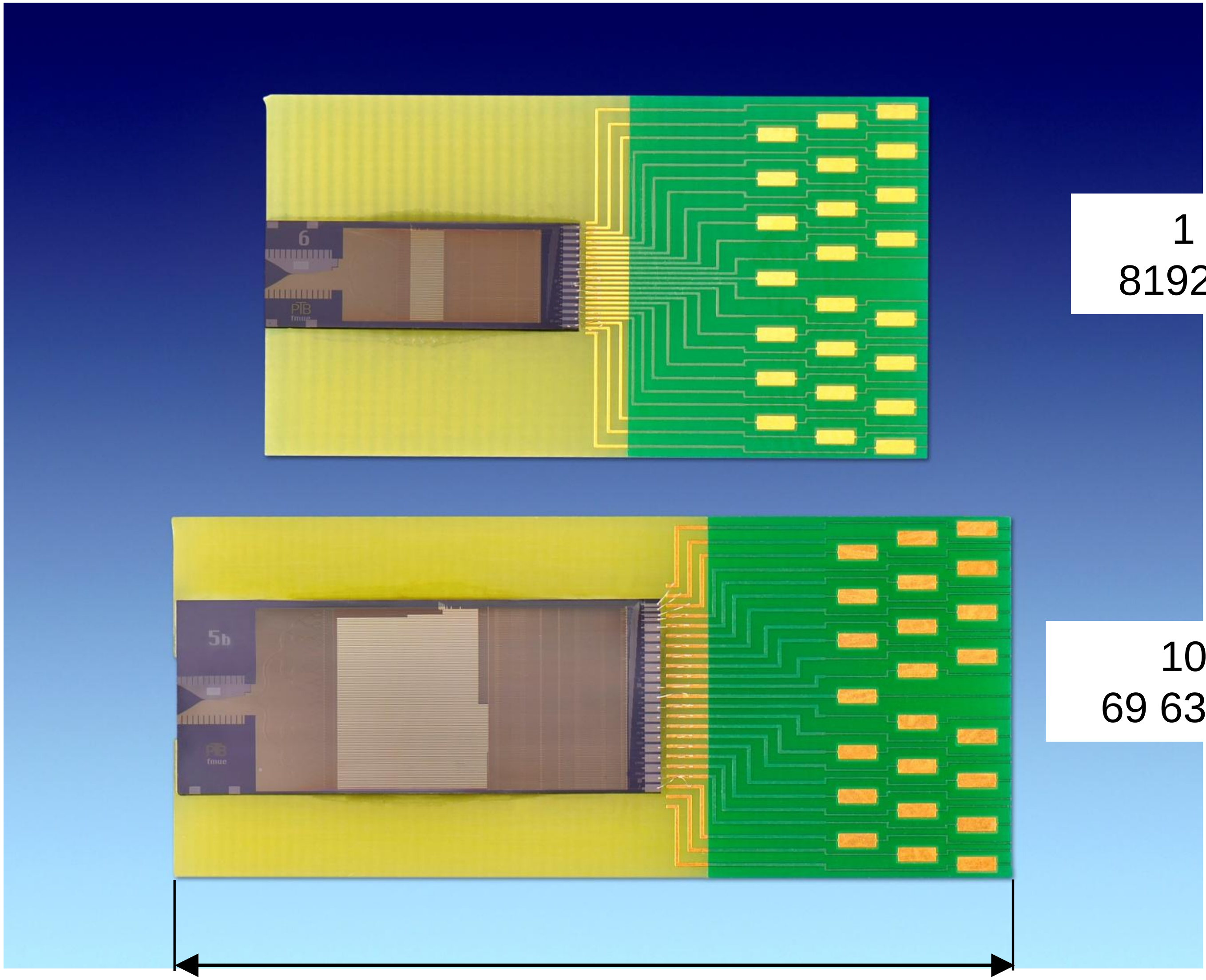


Binary arrays
PJVS
Electrical power
10
1
100m
10m
ADCs
Thermal converters
JAWS
Impedance bridg
Pulse-driven arrays
Dynamic measurements
Amplitude / V
Temperature/
Resistance bridges
Johnson Noise Thermometry
DC
1
10
100
1k
10k
100k
1M
Frequency / Hz

AC Metrology with JVS



Programmable Josephson Voltage Standards

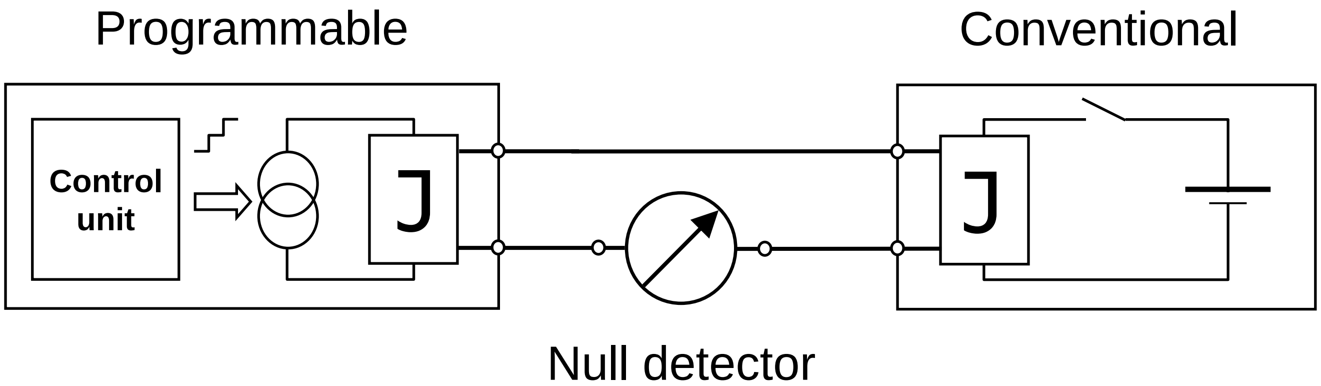


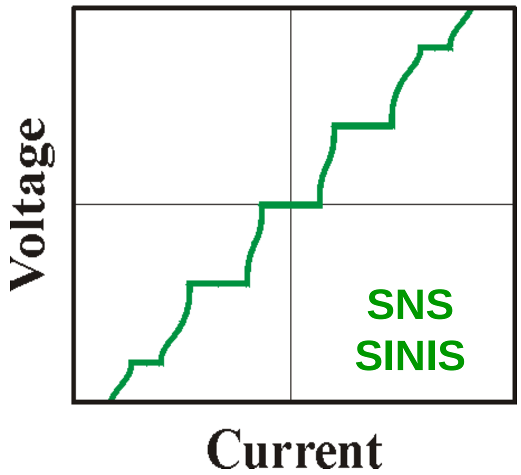
1 V
8192 JJs

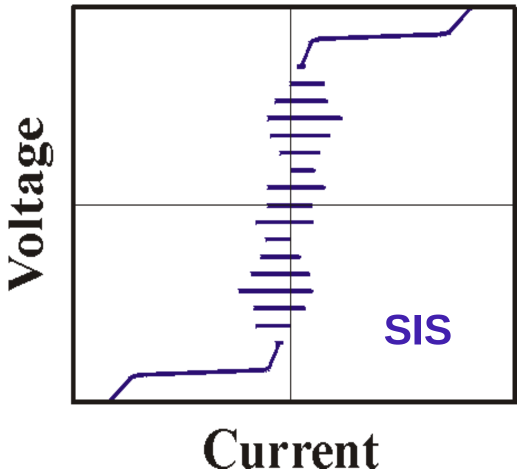
10 V
69 632 JJs

39 mm

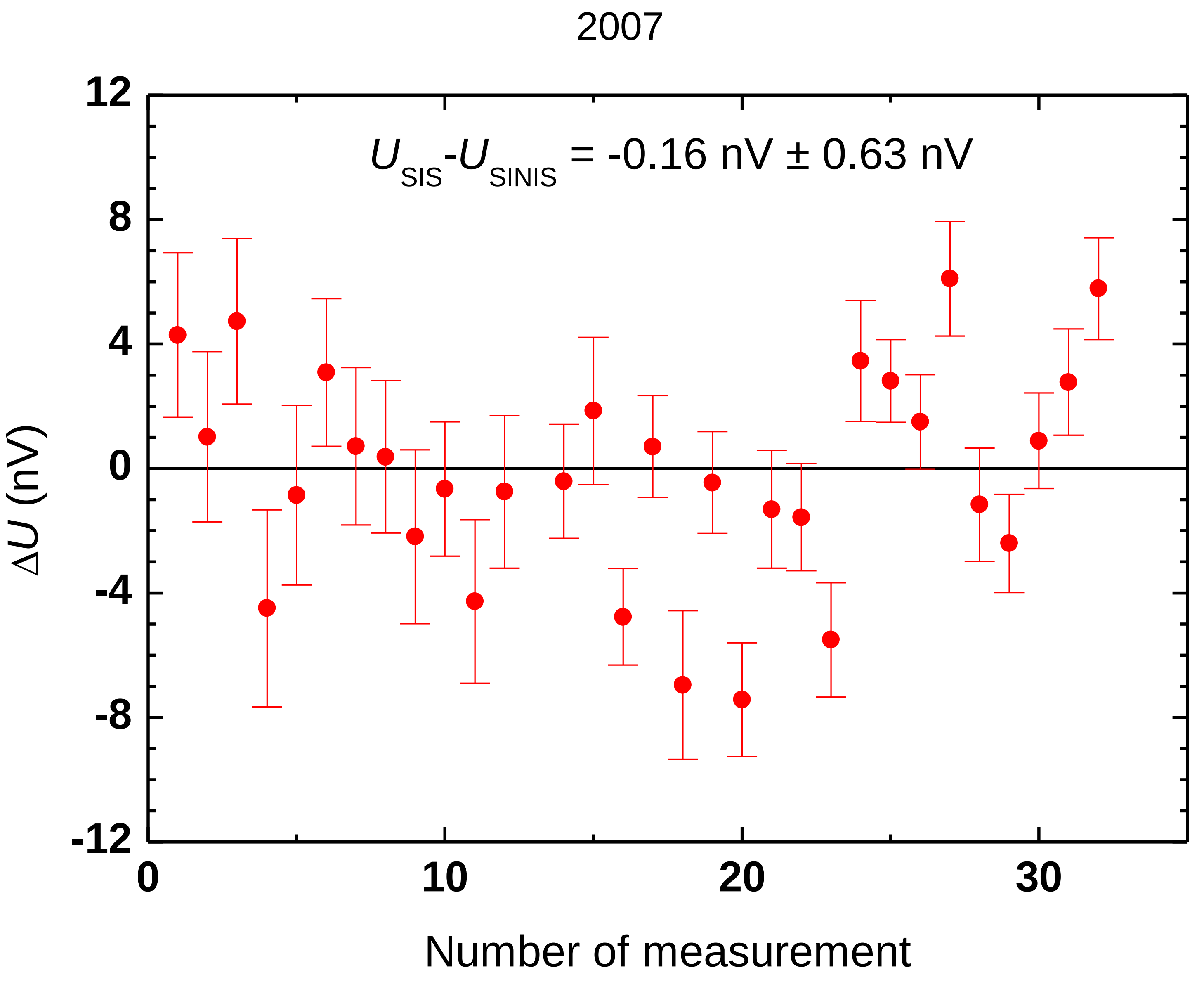
Intercomparison JVS



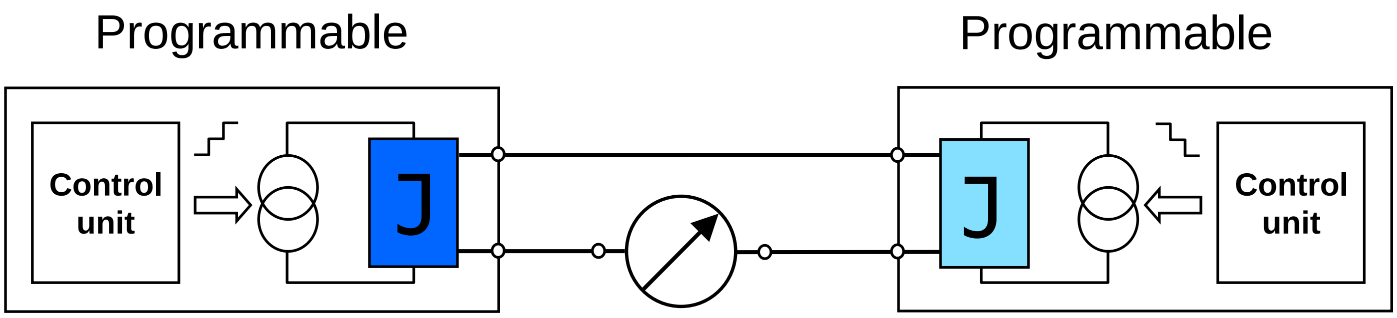


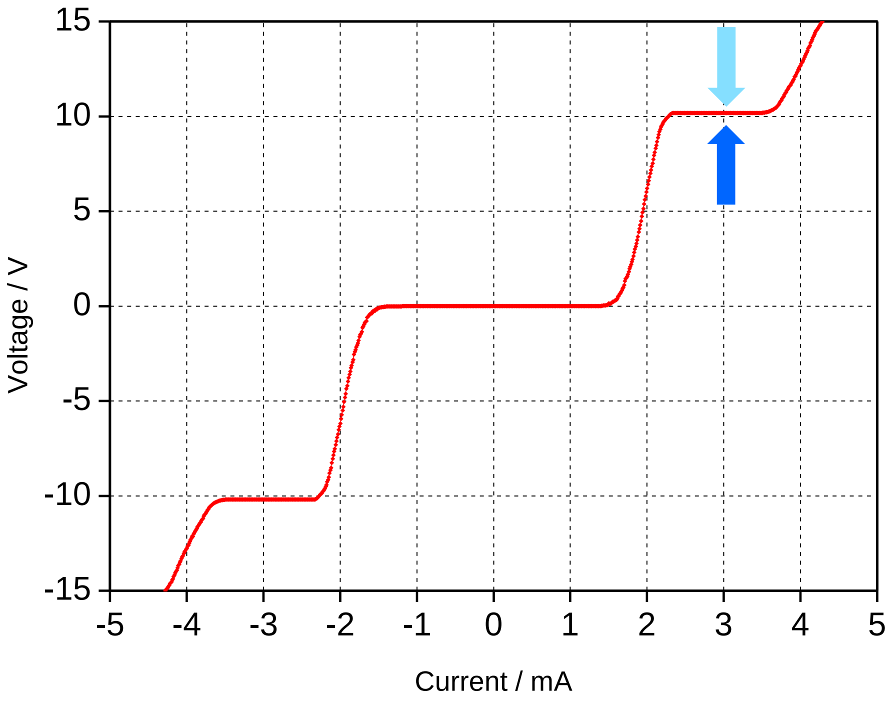


10 V programmable Josephson Arrays

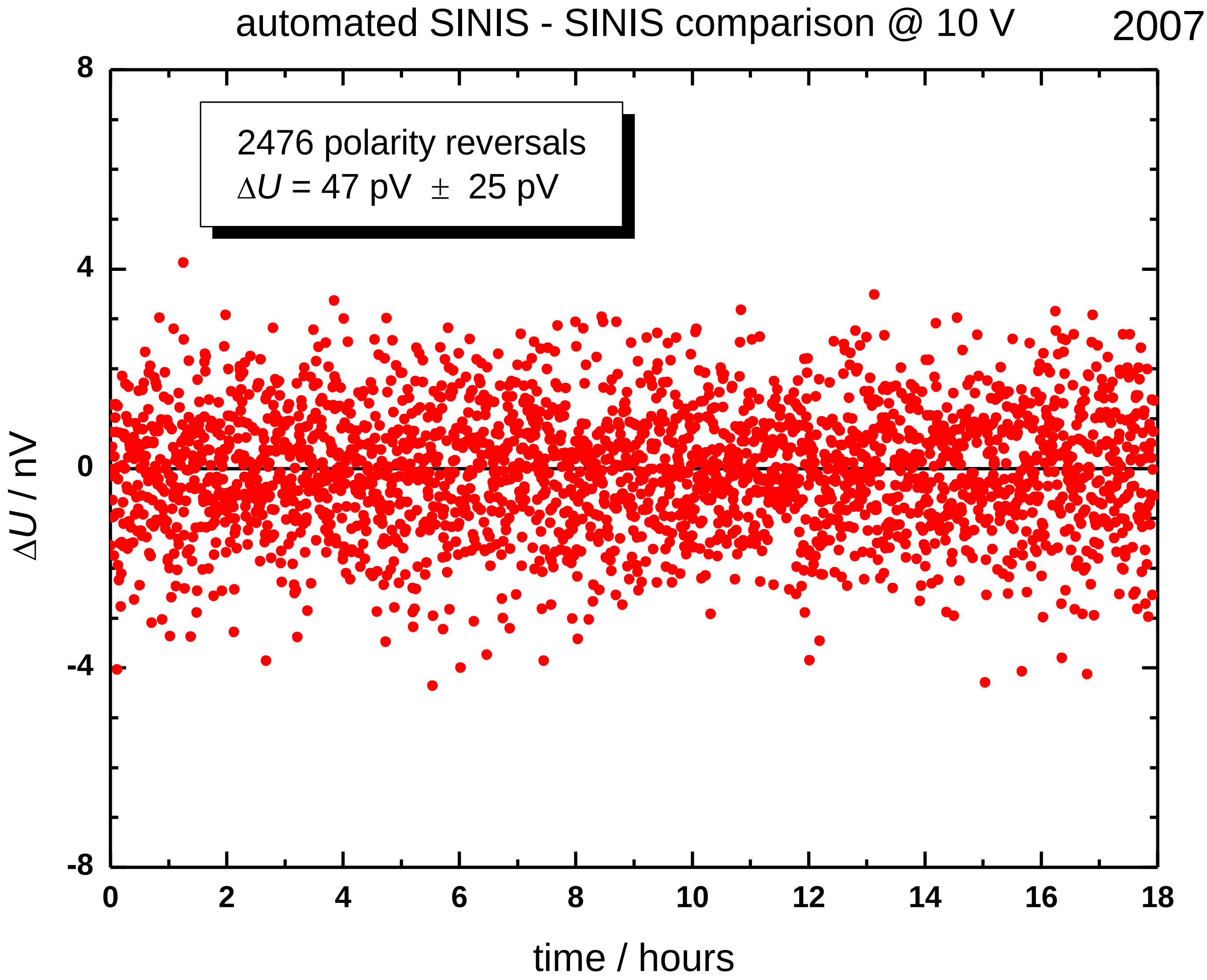


Intercomparison JVS



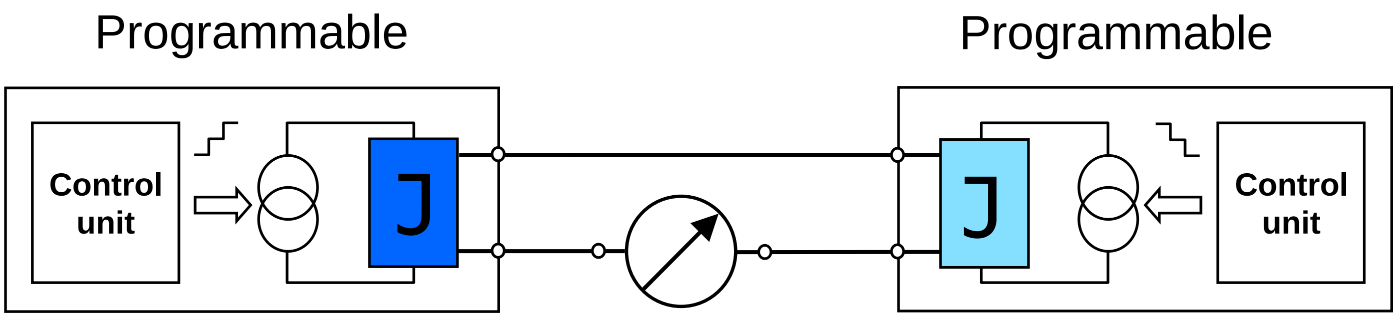


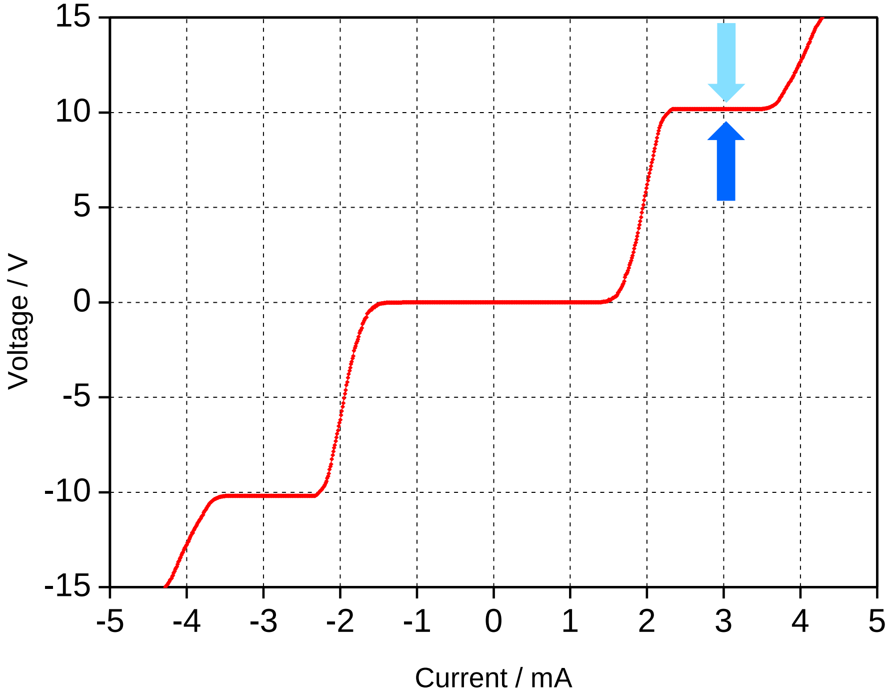
Automated Josephson intercomparison at 10 V



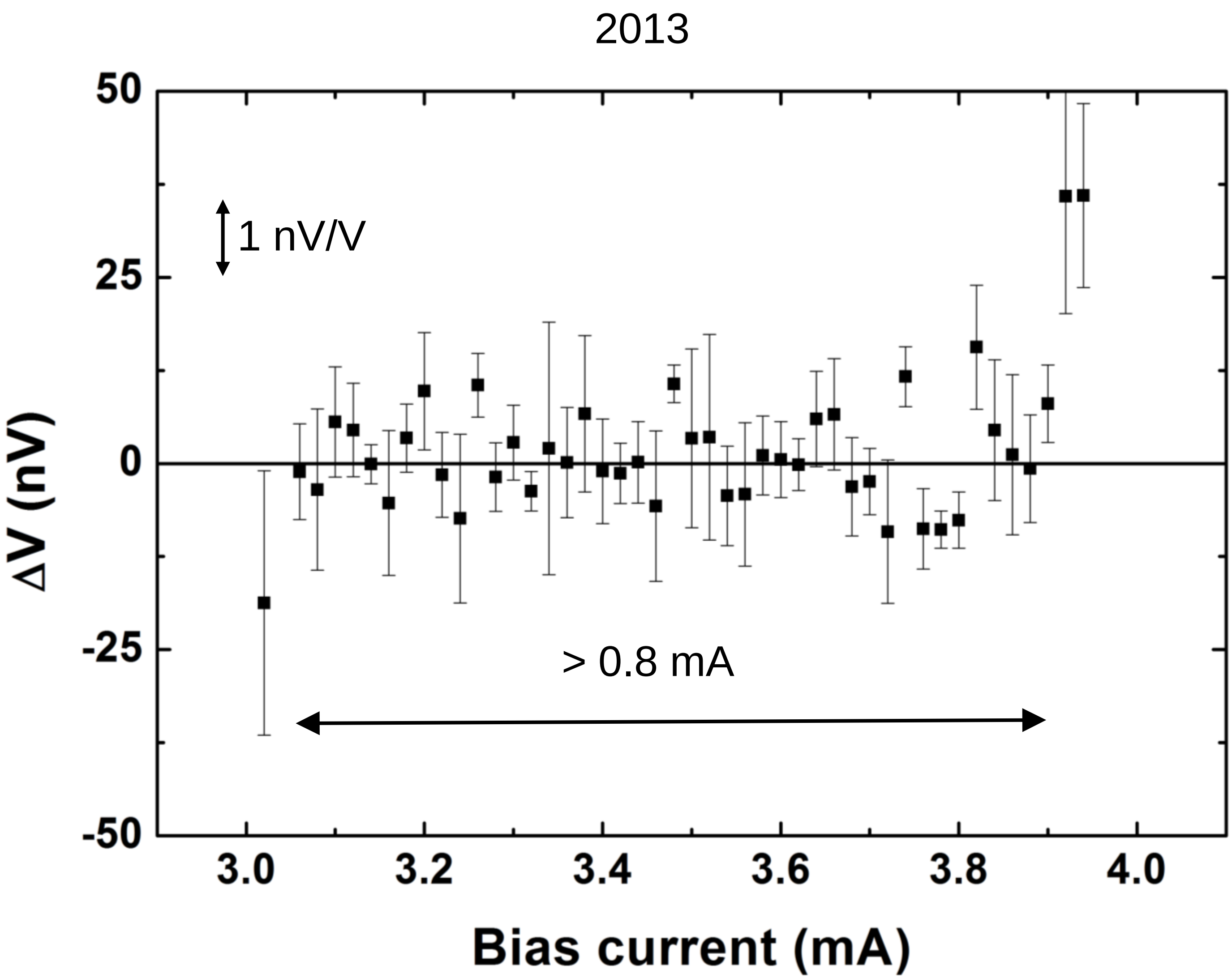
L. Palafox *et al*, *IEEE Tr. Instrum. Meas.*, vol.58, No.4, Apr. 2009

Intercomparison JVS





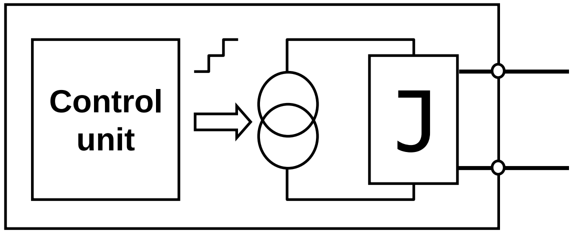
10 V programmable Josephson Arrays



J. Lee *et al*, *Metrologia* 50, 612 (2013)

Automated Josephson DC applications at 10 V

Programmable



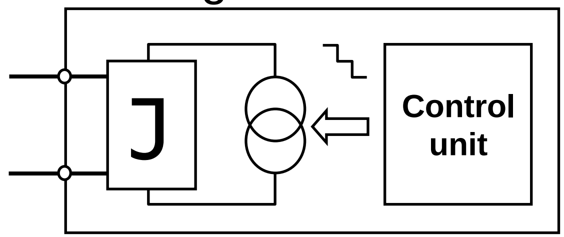
Conventional

DC Gain and linearity

0.1 nV/V

Null detector

Programmable

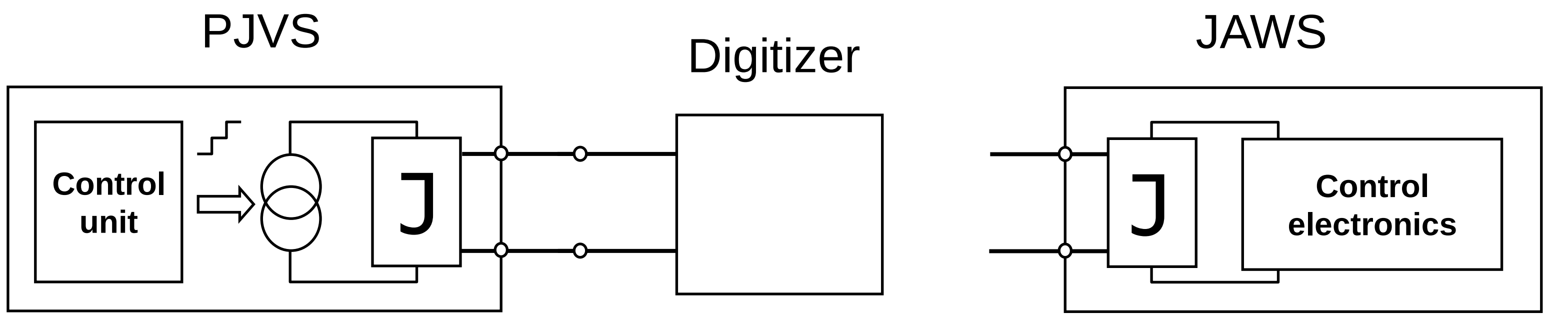


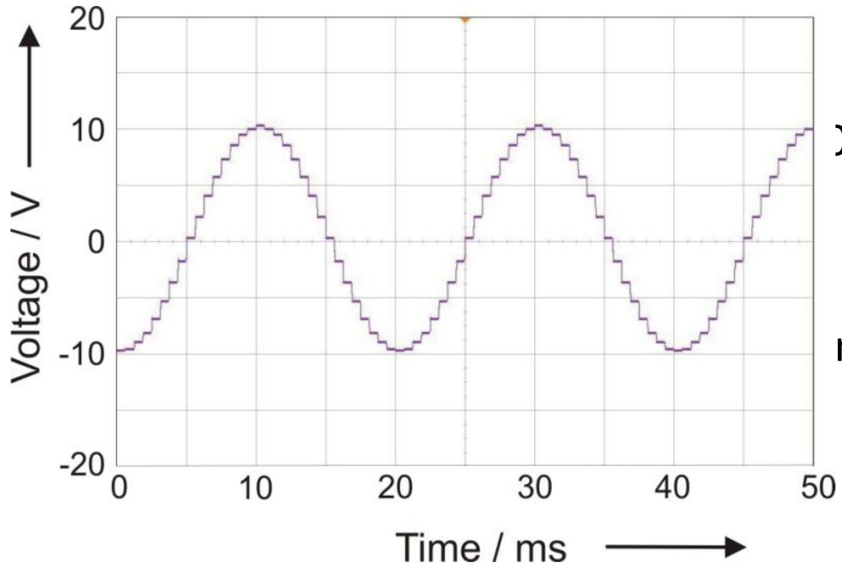
0.1 nV/V

50 nV/V

AC Characterization of DVM/ADCs

Calibrate digitizer and then use it to measure a JAWS





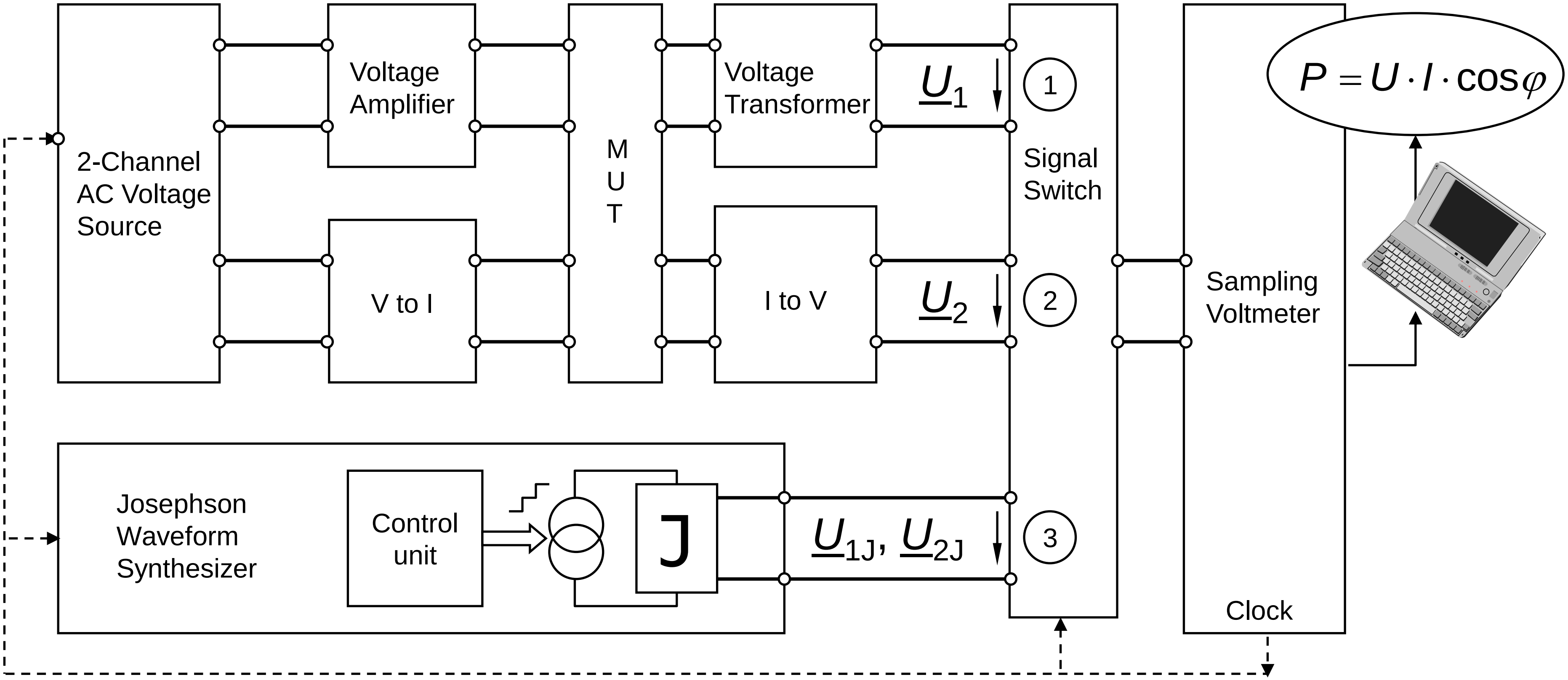
) Hz and 4 kHz

mV at 500 Hz

J. Kohlmann *et al*, *IEEE Tr. Instrum. Meas.,* vol.58, No.4, Apr. 2009

B. Jeanneret *et al*, *Metrologia.,*48, Aug. 2011

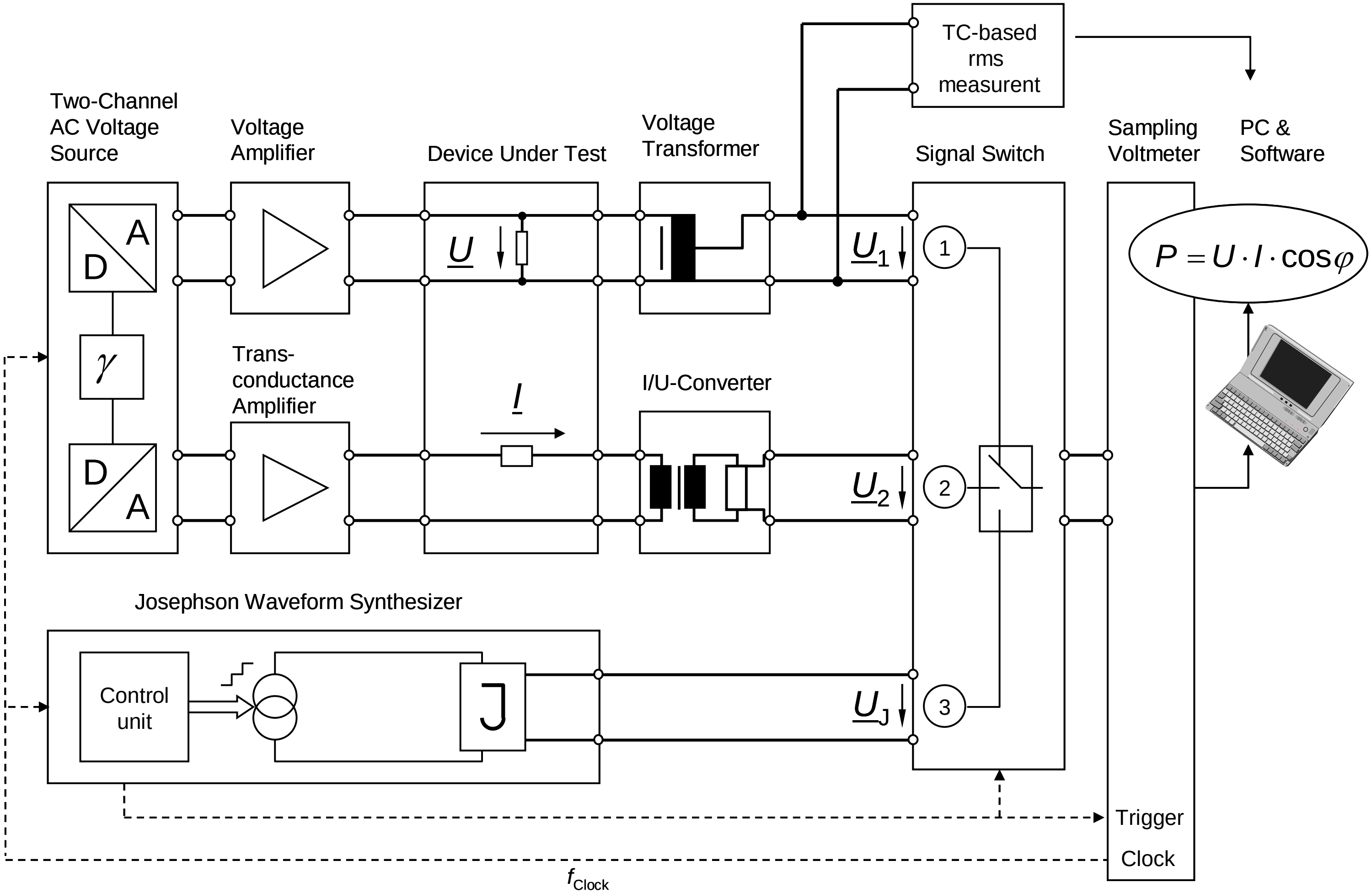
Incorporating a PJVS into a power standard



0.1 µV/V for the RMS value in 1.6 seconds @ 62.5 Hz

L. Palafox *et al*, *IEEE Tr. Instrum. Meas.*, vol.58, No.4, Apr. 2009

Incorporating a PJVS into a power standard

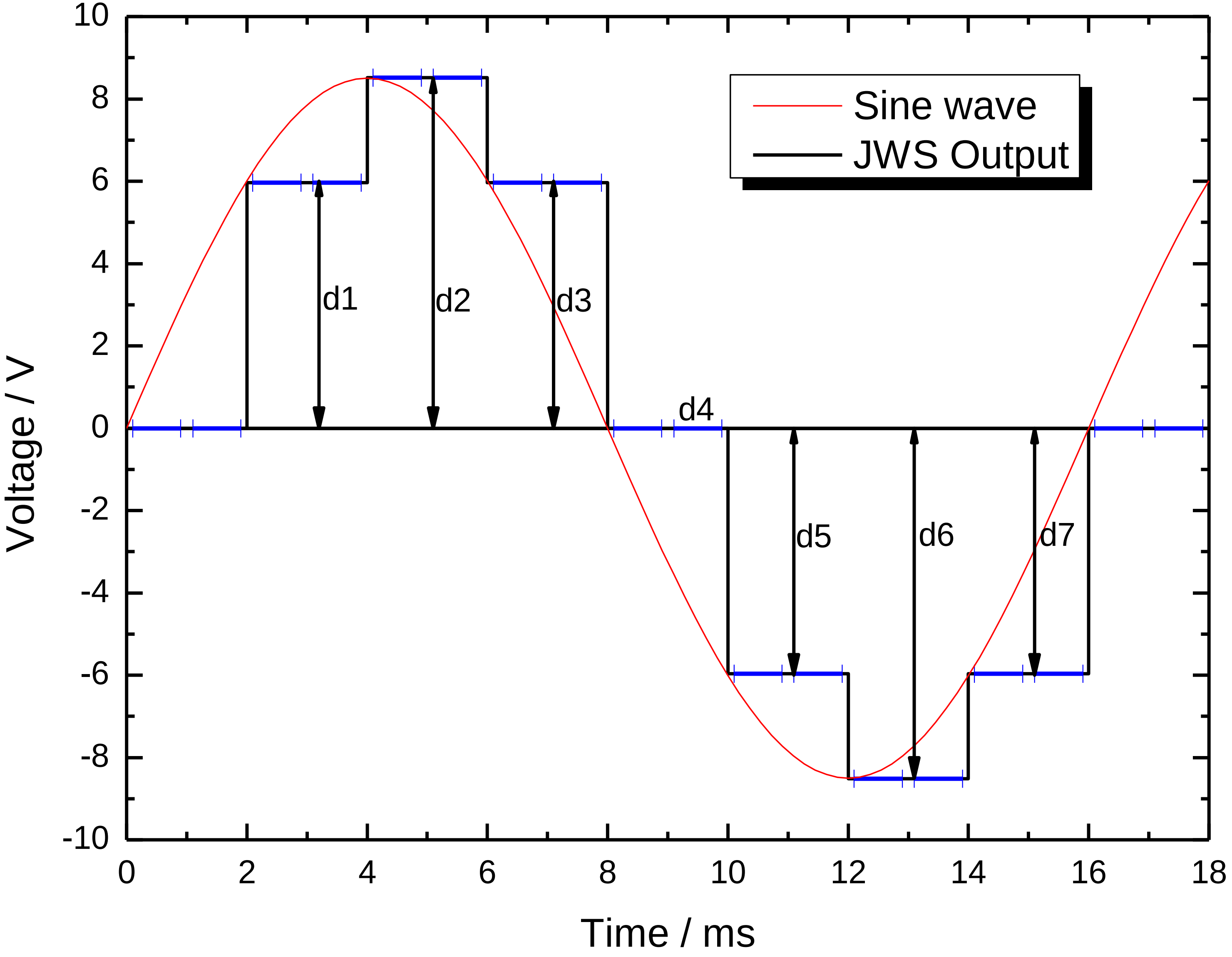


Measuring sequence: U_1, U_2, U_J

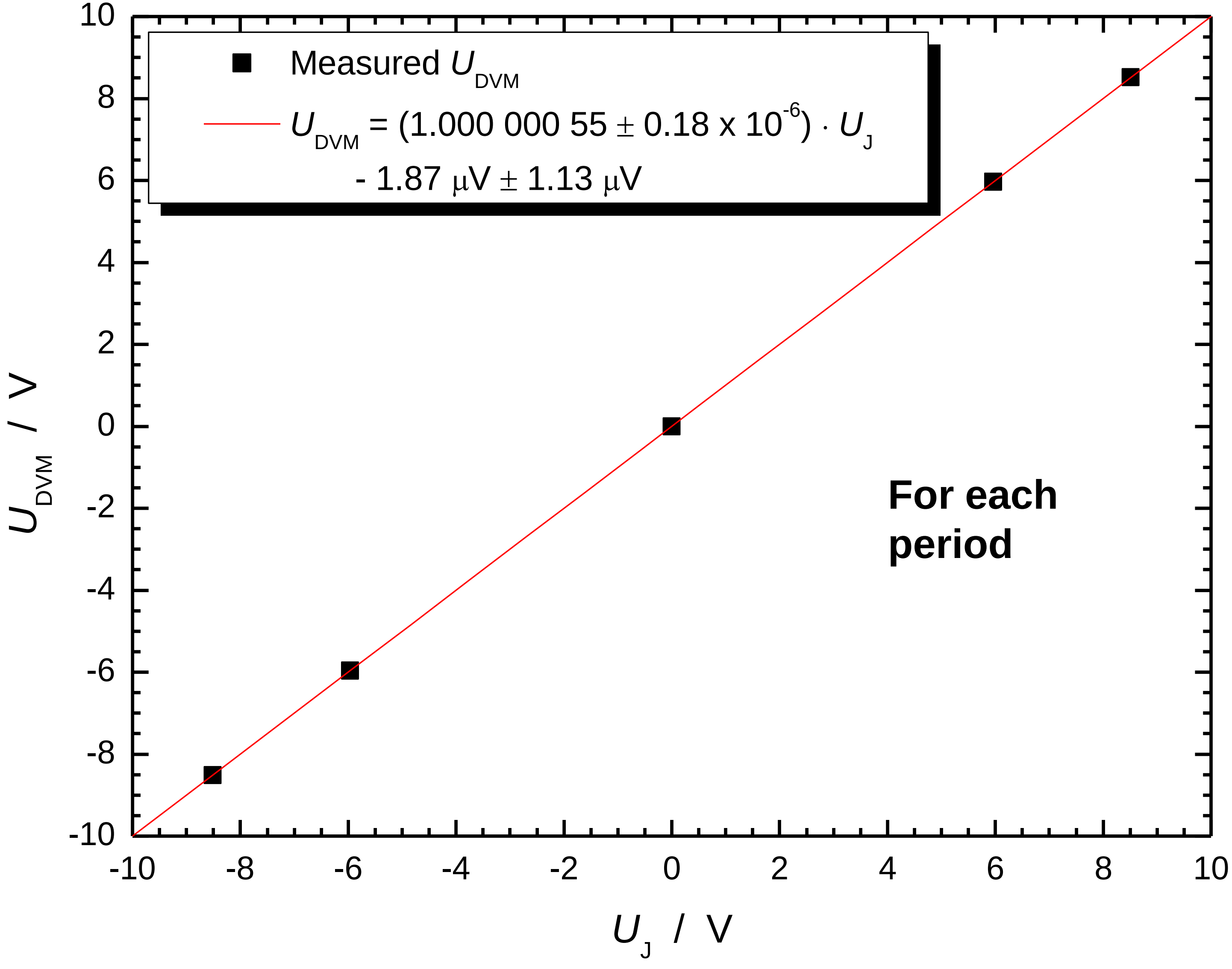
L. Palafox *et al*, *IEEE Tr. Instrum. Meas.*, vol.58, No.4, Apr. 2009

Incorporating a PJVS into a power standard

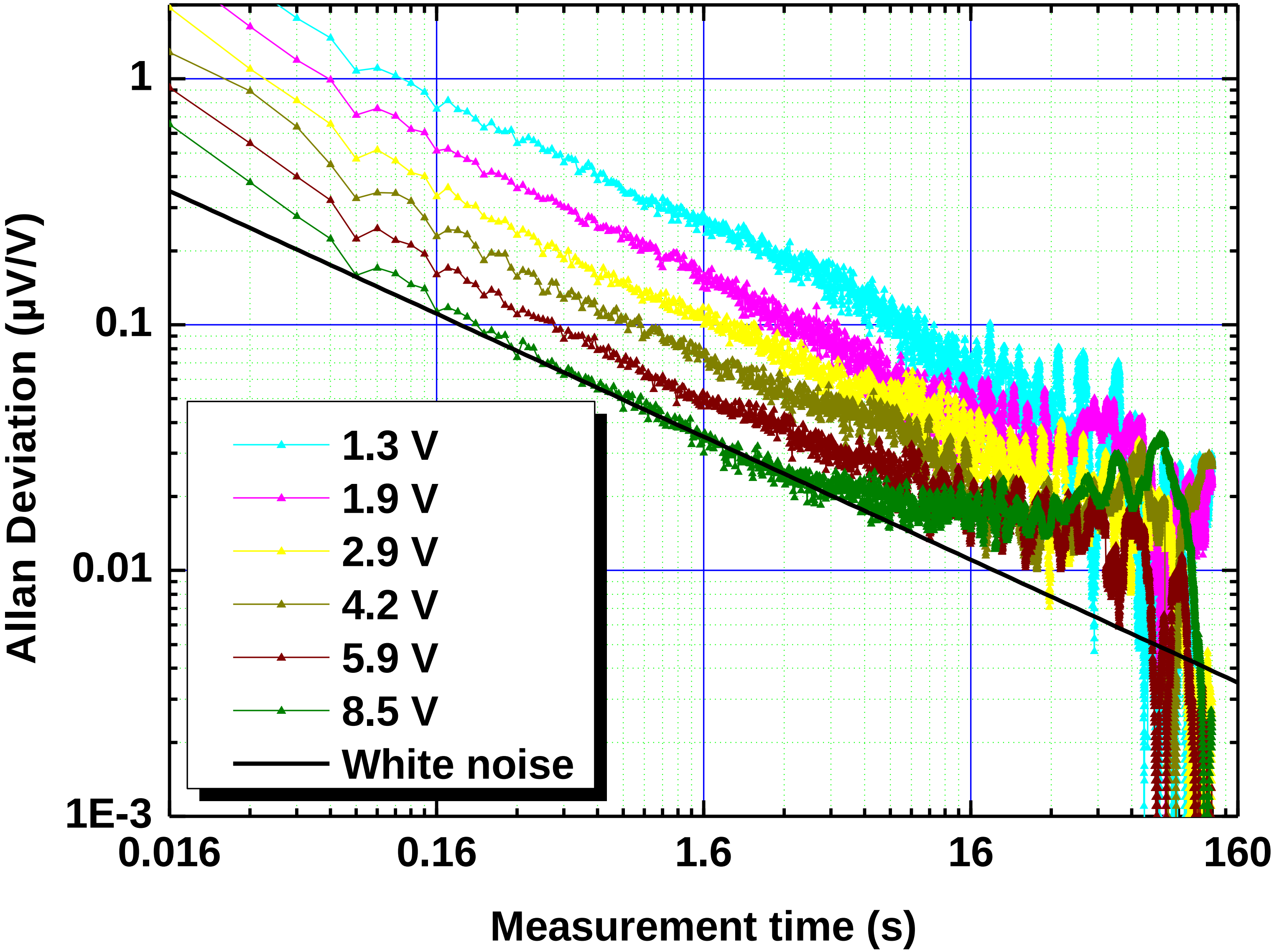
Incorporating a PJVS into a power standard



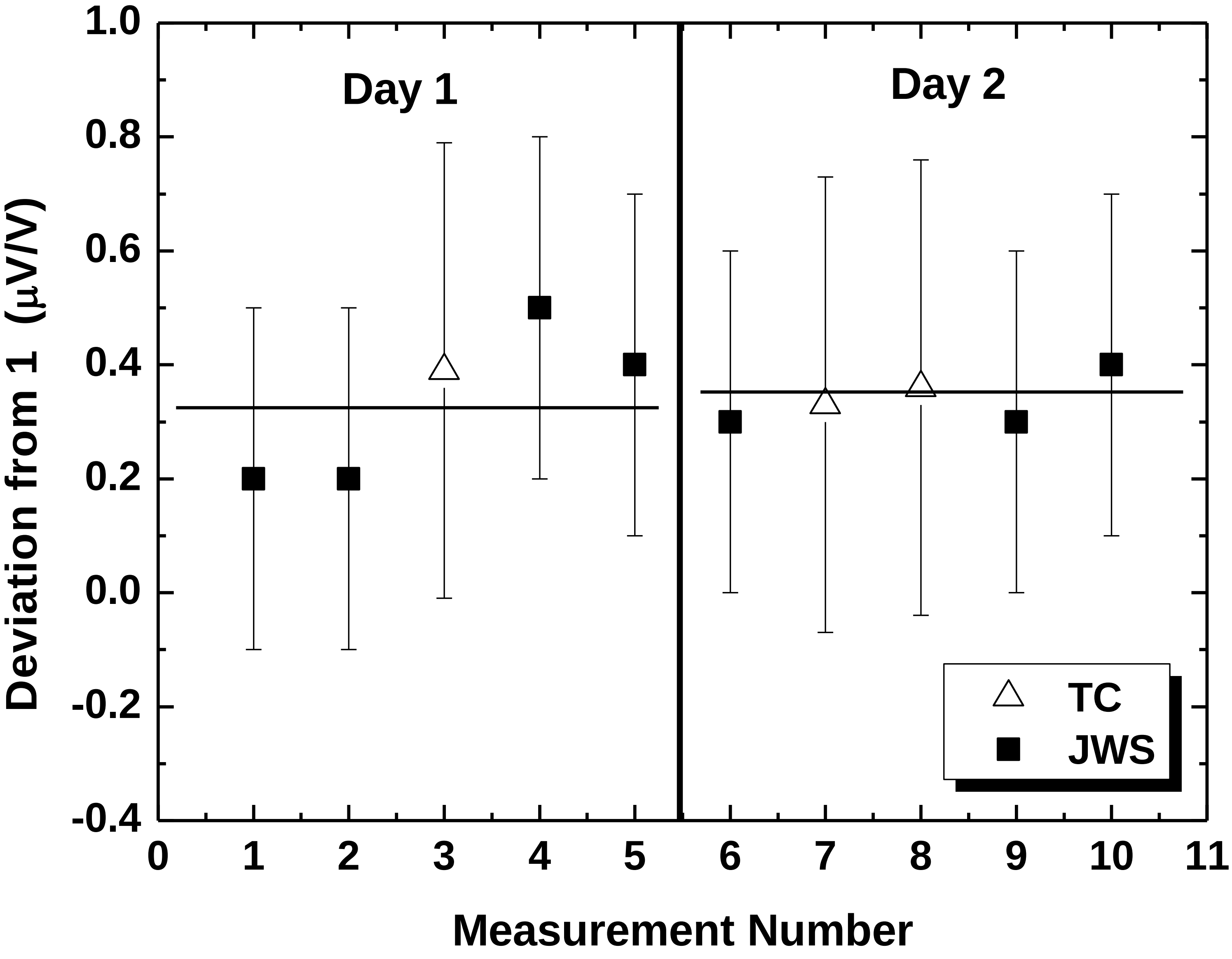
Incorporating a PJVS into a power standard



Incorporating a PJVS into a power standard



Measurement of RMS Value @ 6V



Conclusions (2008)

- Josephson Waveform Synthesizer successfully integrated into the PTB primary standard for electrical power
- Uncertainty, presently 1.1 µW / VA (k=1), dominated by contributions from voltage and current transformers and burden (0.87 / 1.1) µW / VA
- In-situ calibration of sampling DVM considerably speeds up precise measurements of rms value.
- Generation of Josephson waveforms with any amplitude up to 10 V allows matching any measurement condition
- Direct traceability to unit volt

Conclusions (2012)

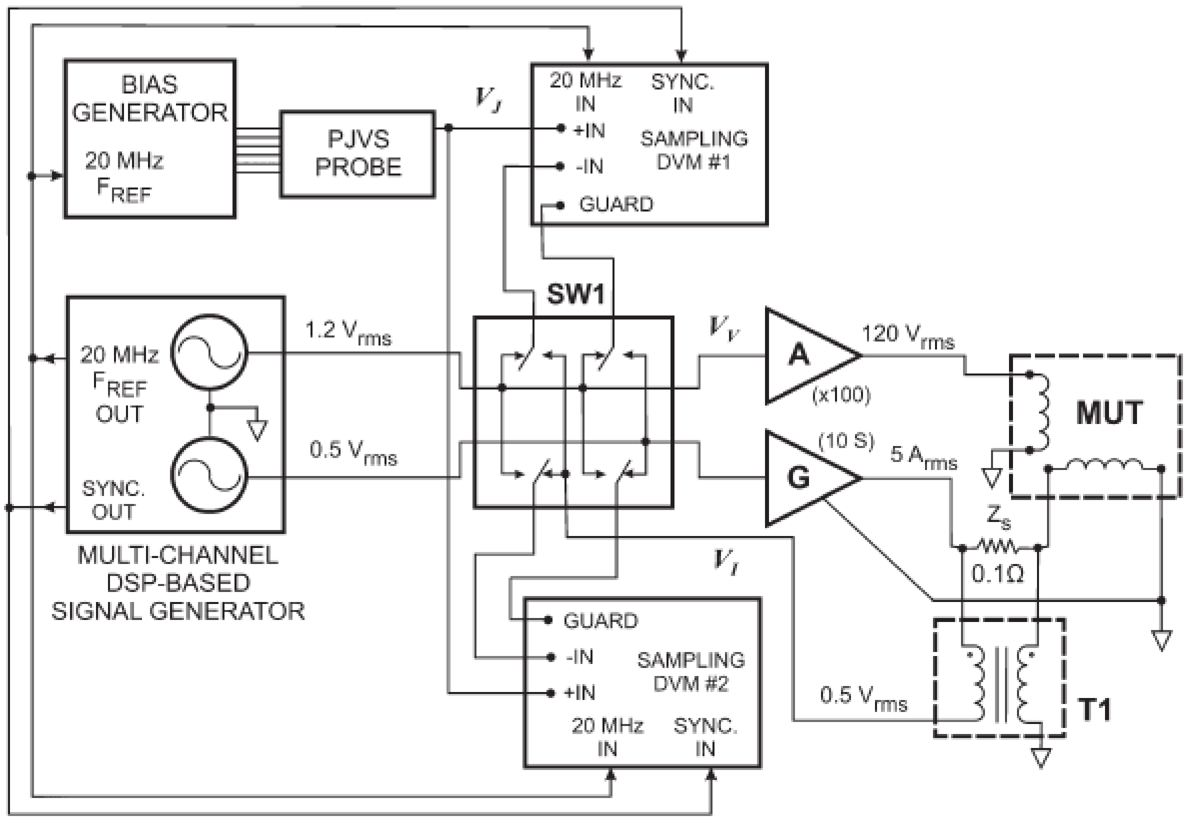
- Josephson calibration of DVM / Digitizer in "direct / absolute sampling mode" at
- 62.5 Hz 0.1 µV/V in 1.6 seconds
- up to 1.3 kHz 8 µV/V in 0.1 seconds

  - NOT limited by the PJVS!!

Other power standards with Josephson

- NIST
  Waltrip *et al.* IEEE Tr. IM 58, No. 4, 1041 - 1048
- NRC
  Djokić, IEEE Tr. IM 62, No. 6, 1699 - 1703
- KRISS
  Kim *et al.* , Meas. Sci. Technol., 21 115102

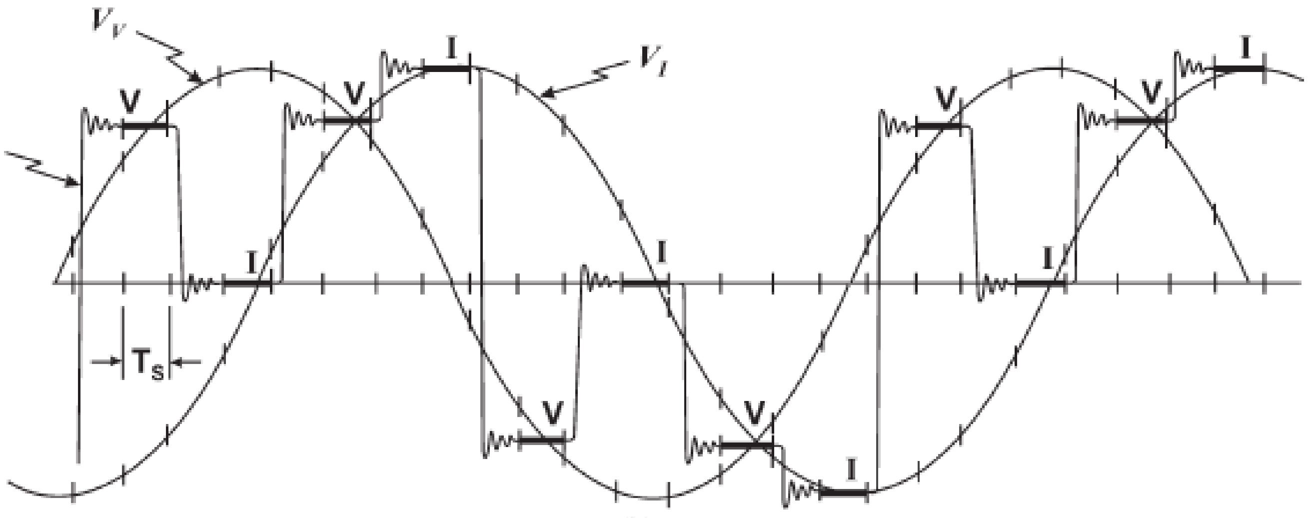
NIST Power standard



(a)

Waltrip *et al.* IEEE Tr. IM 58, No. 4, 1041 - 1048

NIST Power standard



(b)

Fig. 1. Quantum-based power generation system. (a) Simplified diagram, including sampling DVMs operating in the differential voltage sampling mode. (b) How a single PJVS waveform V_J is used to provide reference levels for the differential sampling of the two scaled voltages V_V and V_I. The bold intervals of V_J represent the sampling intervals of interest; the remaining sampling intervals are ignored.

Waltrip *et al.* IEEE Tr. IM 58, No. 4, 1041 - 1048

NIST Power standard

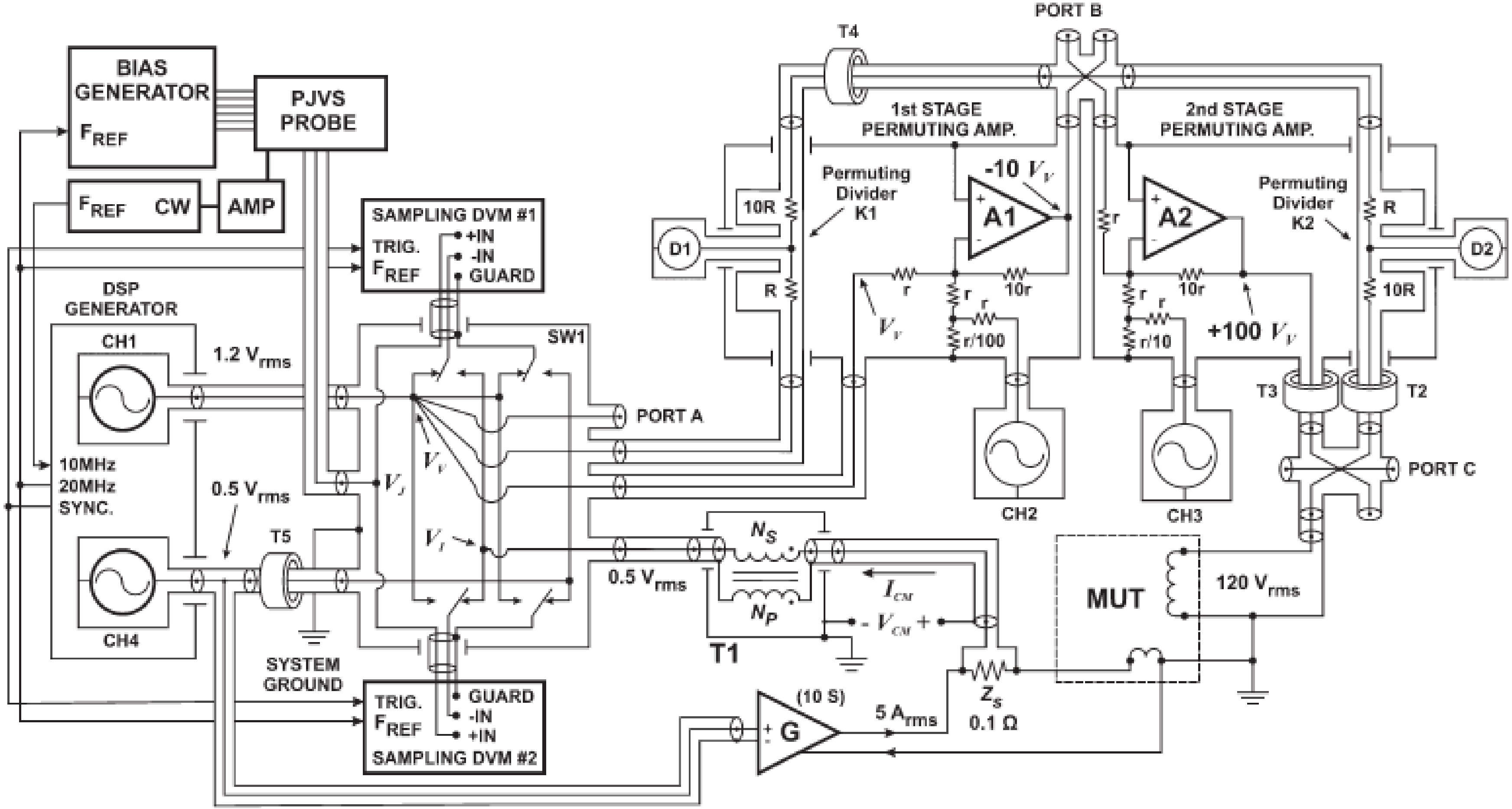
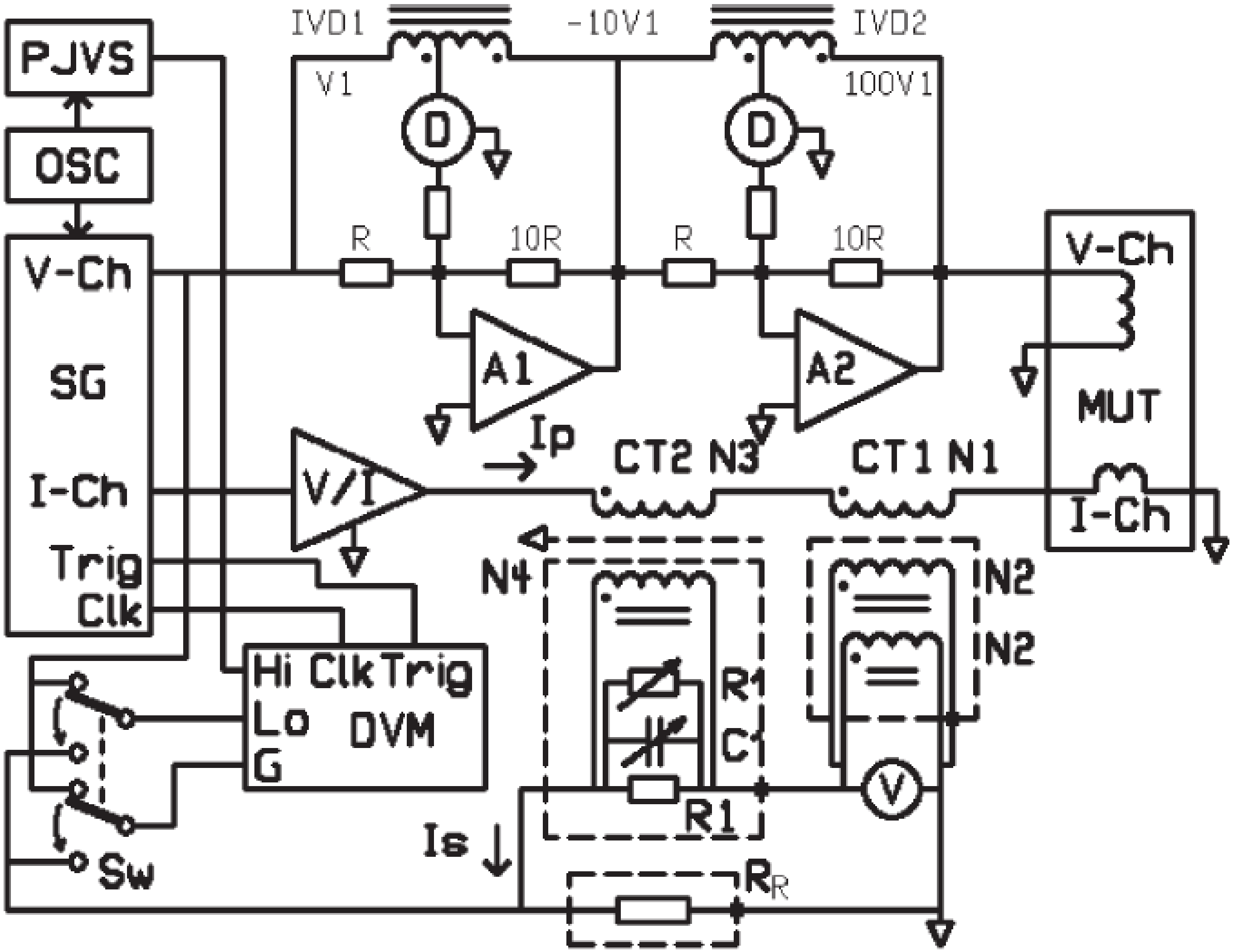


Fig. 5. Detailed diagram of the quantum-based power generation system detailing the permuting amplifier design and component interconnection requirements.

Waltrip *et al.* IEEE Tr. IM 58, No. 4, 1041 - 1048

NRC Power standard



Djokic, IEEE Tr. IM 62, No. 6, 1699 – 1703 (2013)

KRISS Power standard

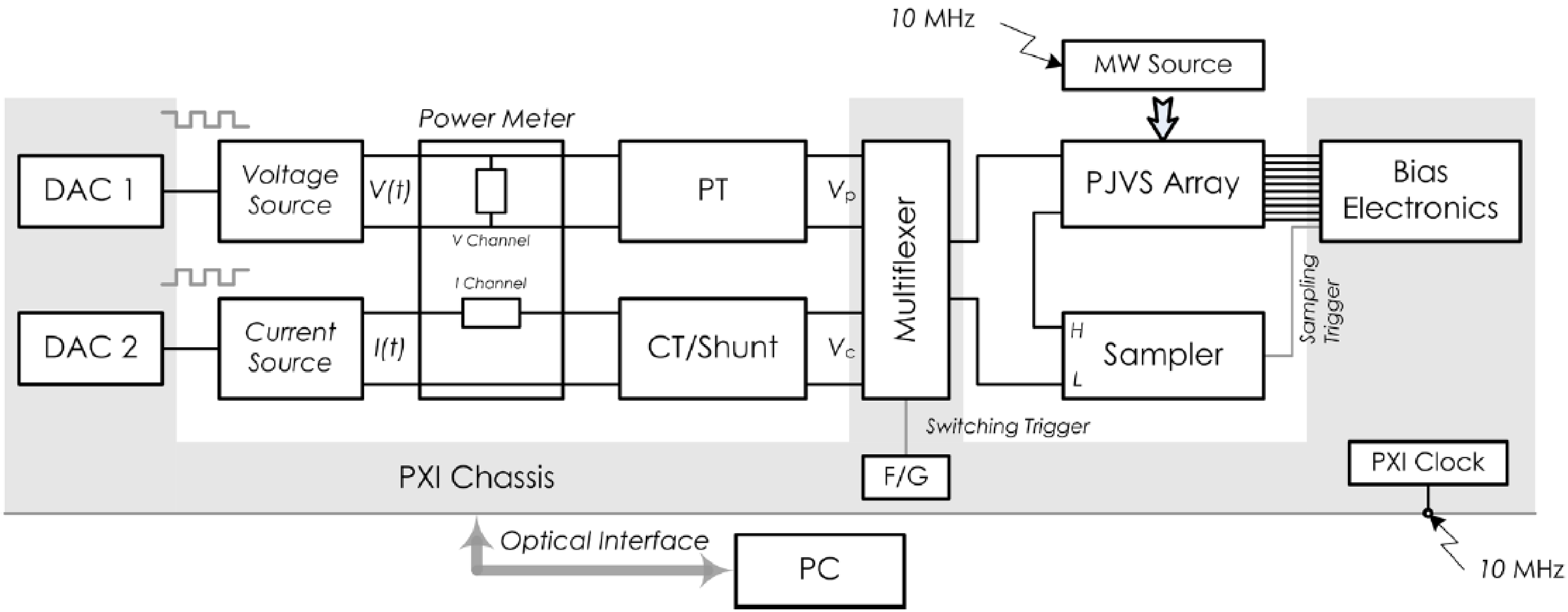


Fig. 1. Schematic diagram of power calibration system based on Josephson sampling voltmeter.

Kim *et al.*, CPEM 2014 Digest, 738-739

Thank you very much for your attention!

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www.ptb.de

NPL National Physical Laboratory

Quantum voltage metrology - instrumentation

Jonathan Williams

23 June 2015

ACQ-PRO Kick-off meeting, PTB, Braunschweig

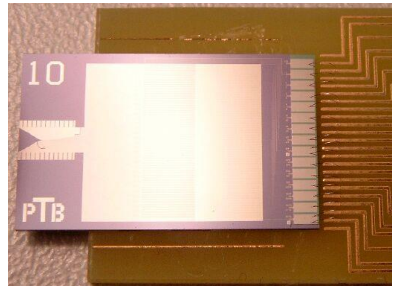
National Measurement System

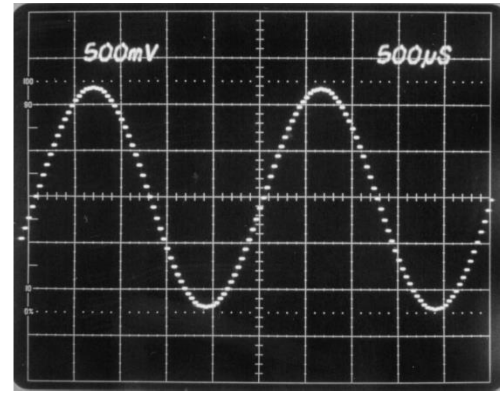
NPL
National Physical Laboratory

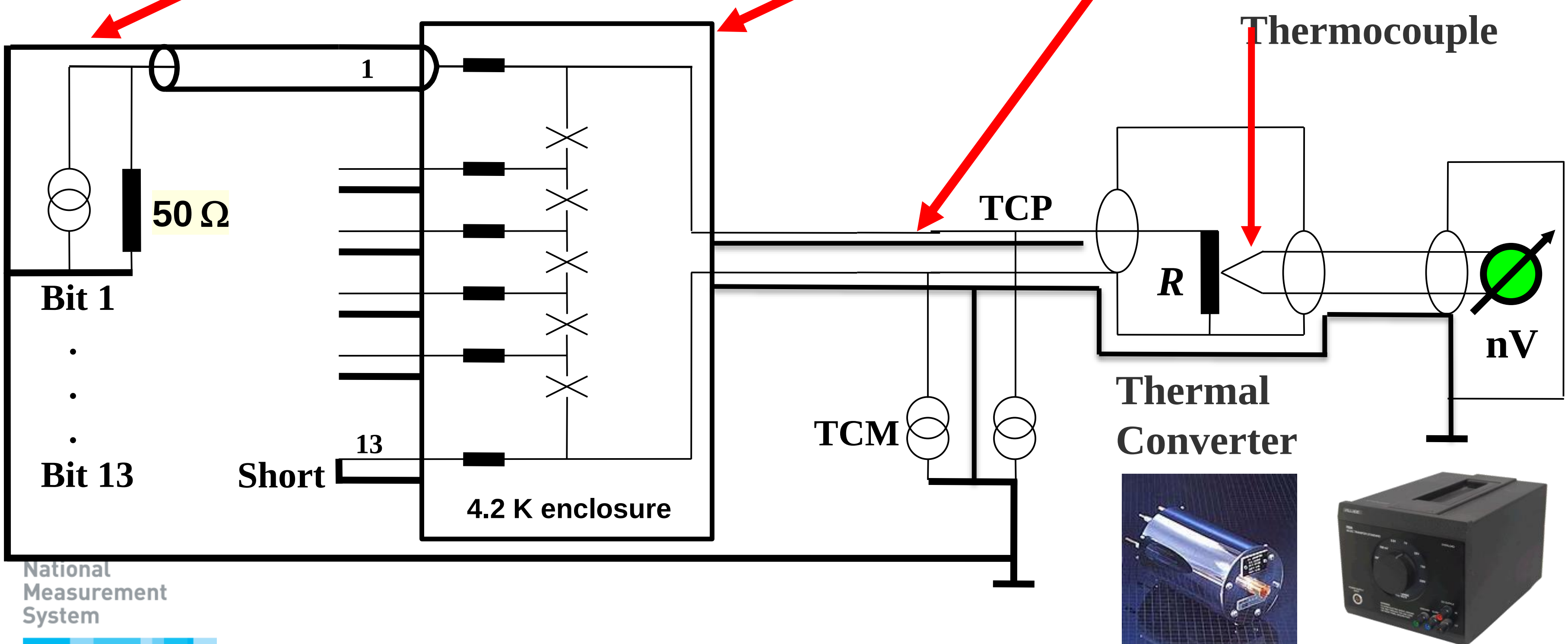
Instruments – top level devices used for metrology

National
Measurement
System

Programmable binary-divided array configured as a DAC – for rms devices

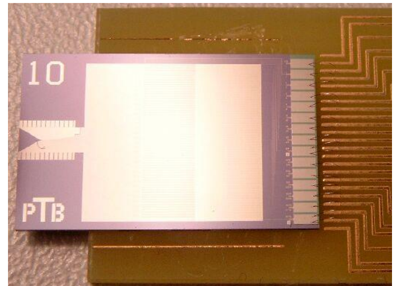


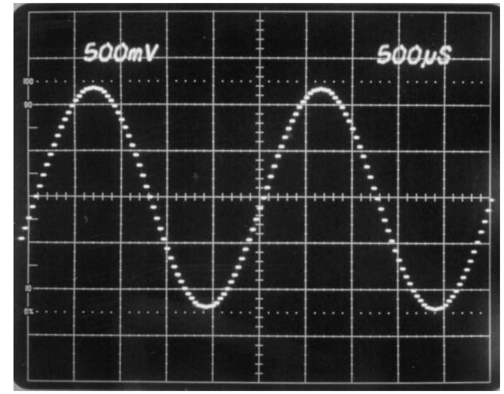


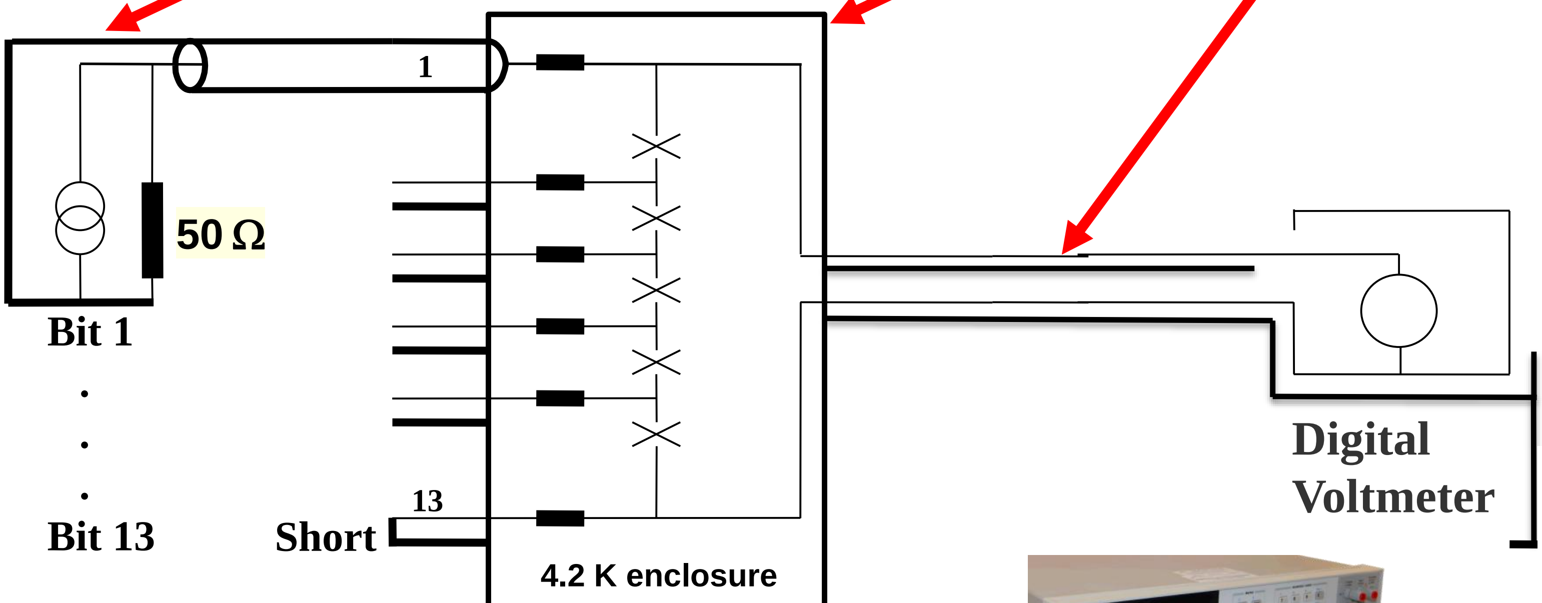


National Physical Laboratory

Programmable binary-divided array configured as a DAC – for sampling devices







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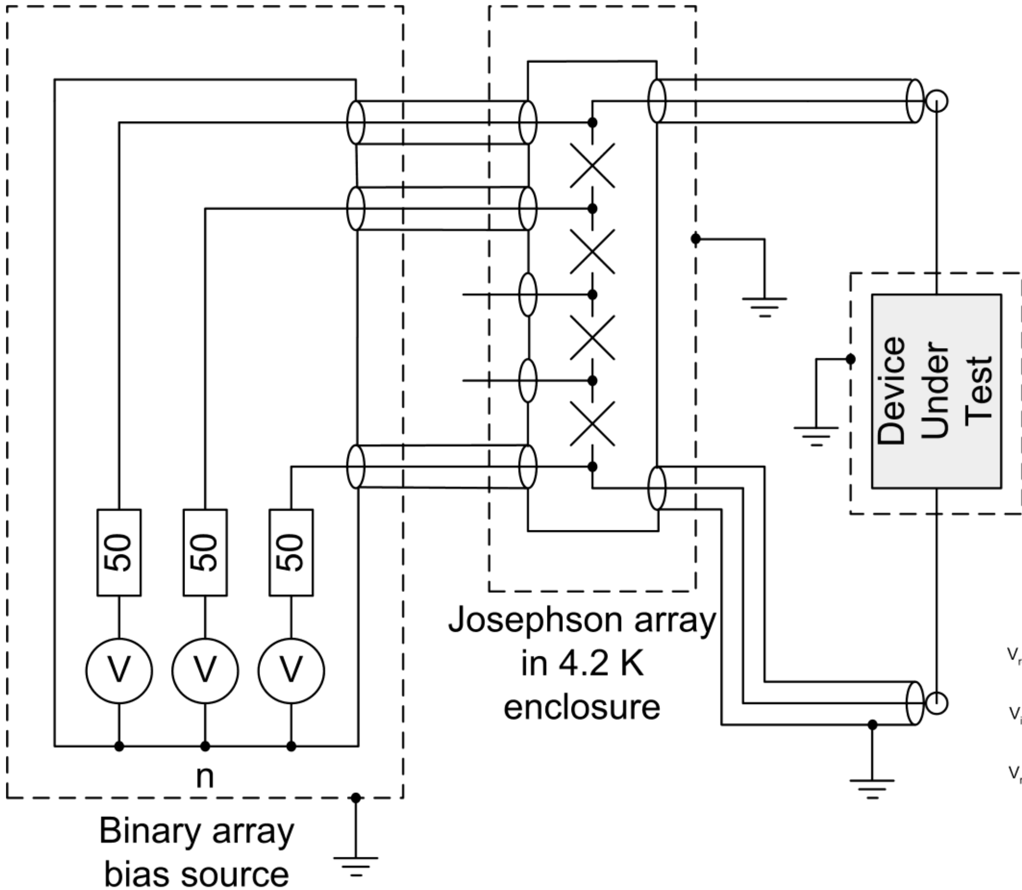
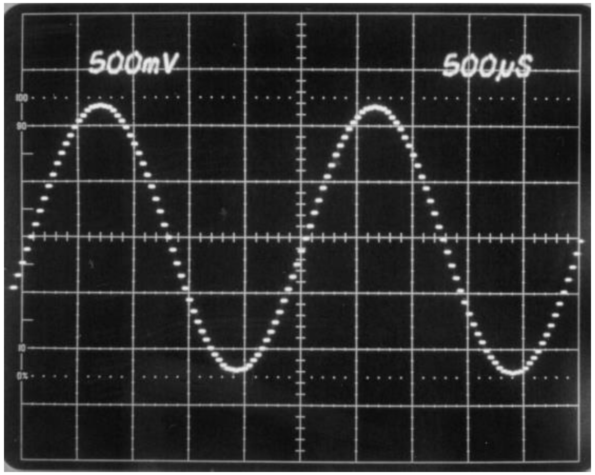
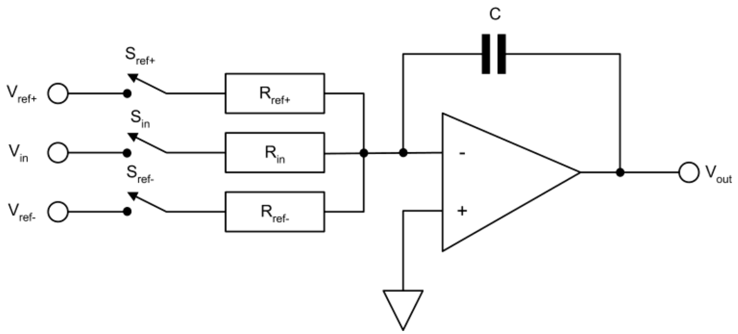
Characterisation of a voltmeter or digitizer

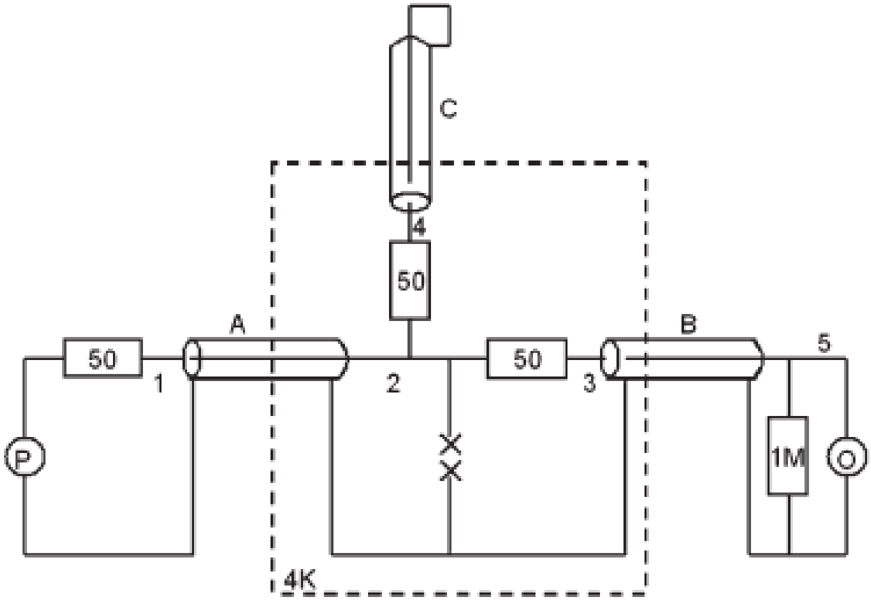


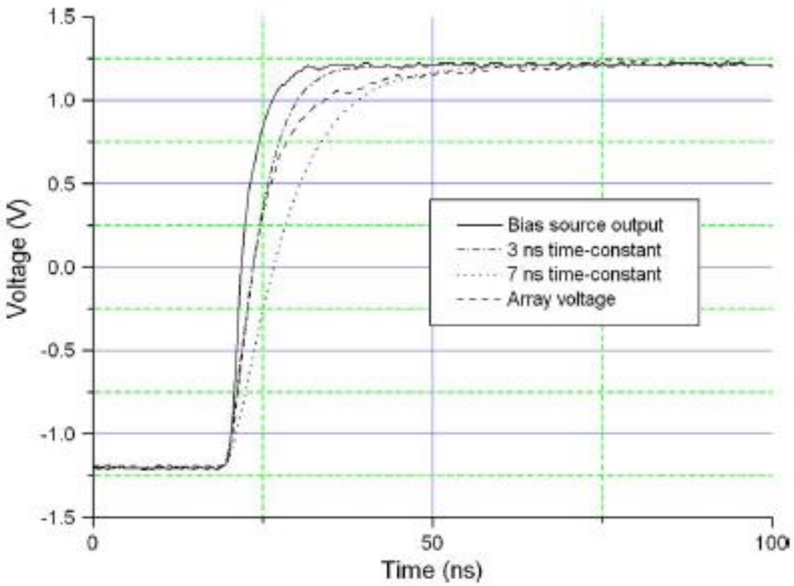




Henderson et al, *Measurement Science & Technology*, **23**, 124006, 2012

Cable reflections – compensation method





Williams et al, *IEEE Trans Instrum Meas*, **56**, 651-654, 2007

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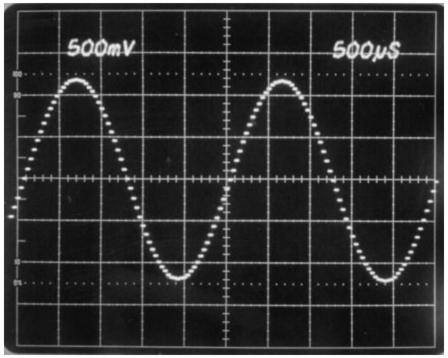
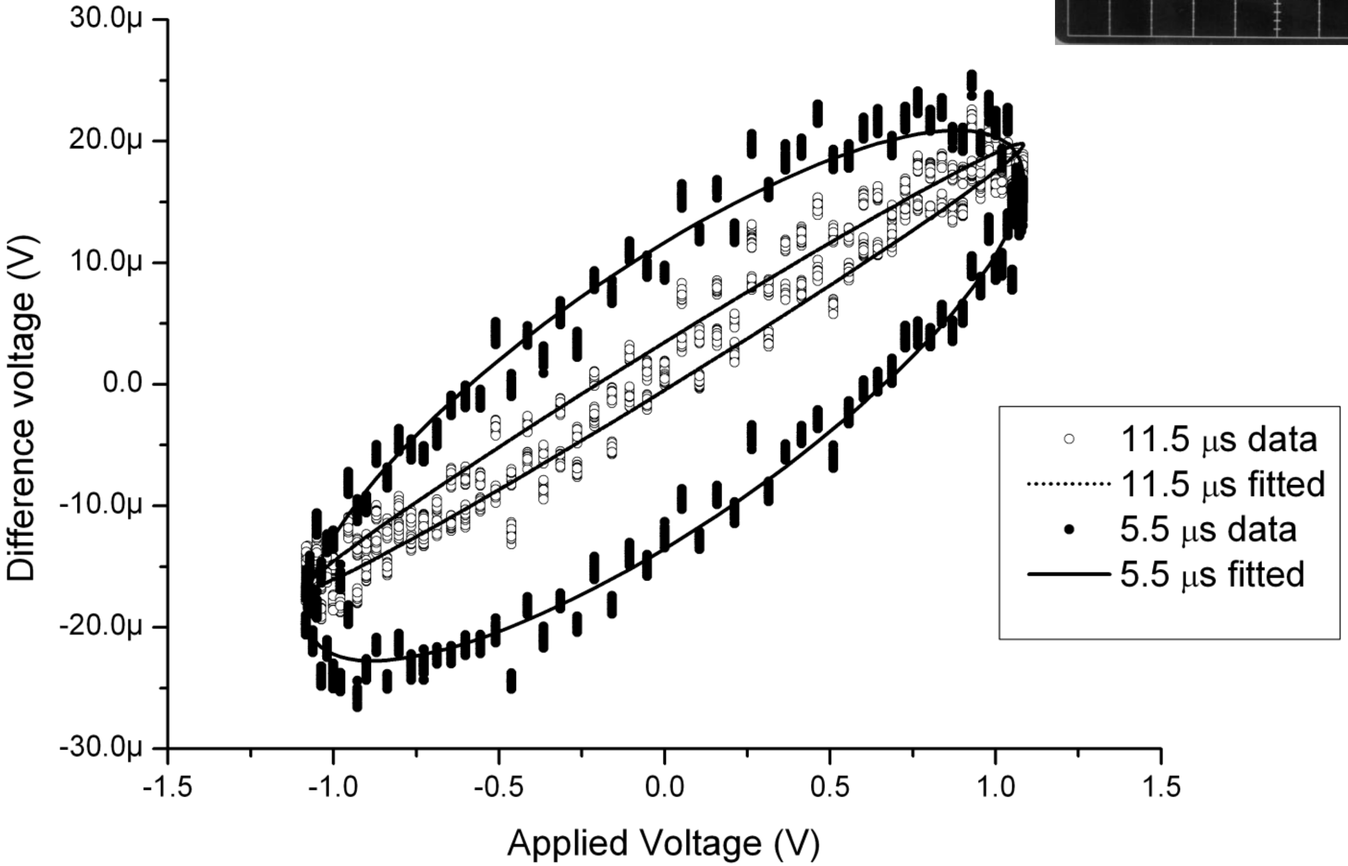
Data analysis – gain, time constant and linearity





Henderson et al, *Measurement Science & Technology*, **23**, 124006, 2012

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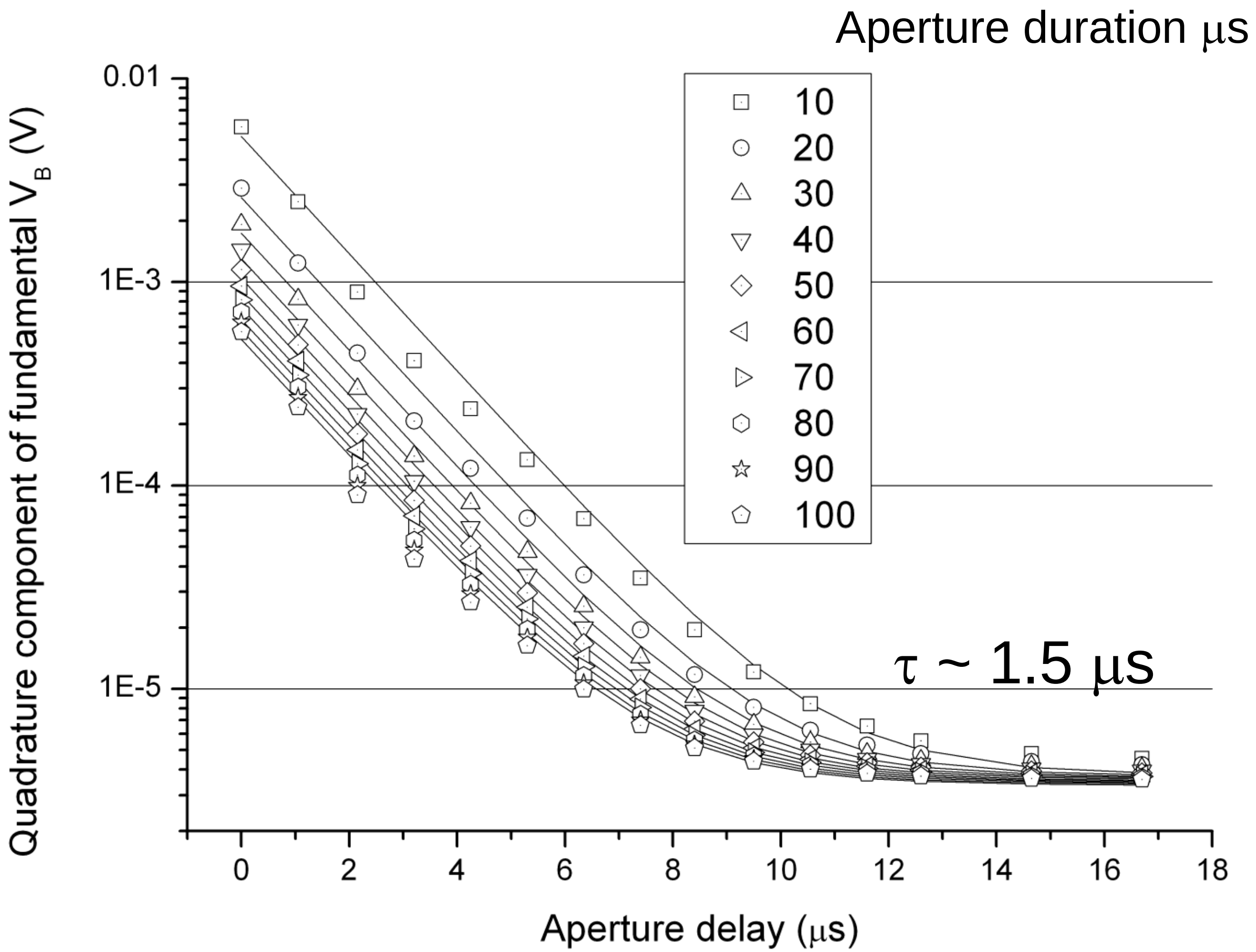
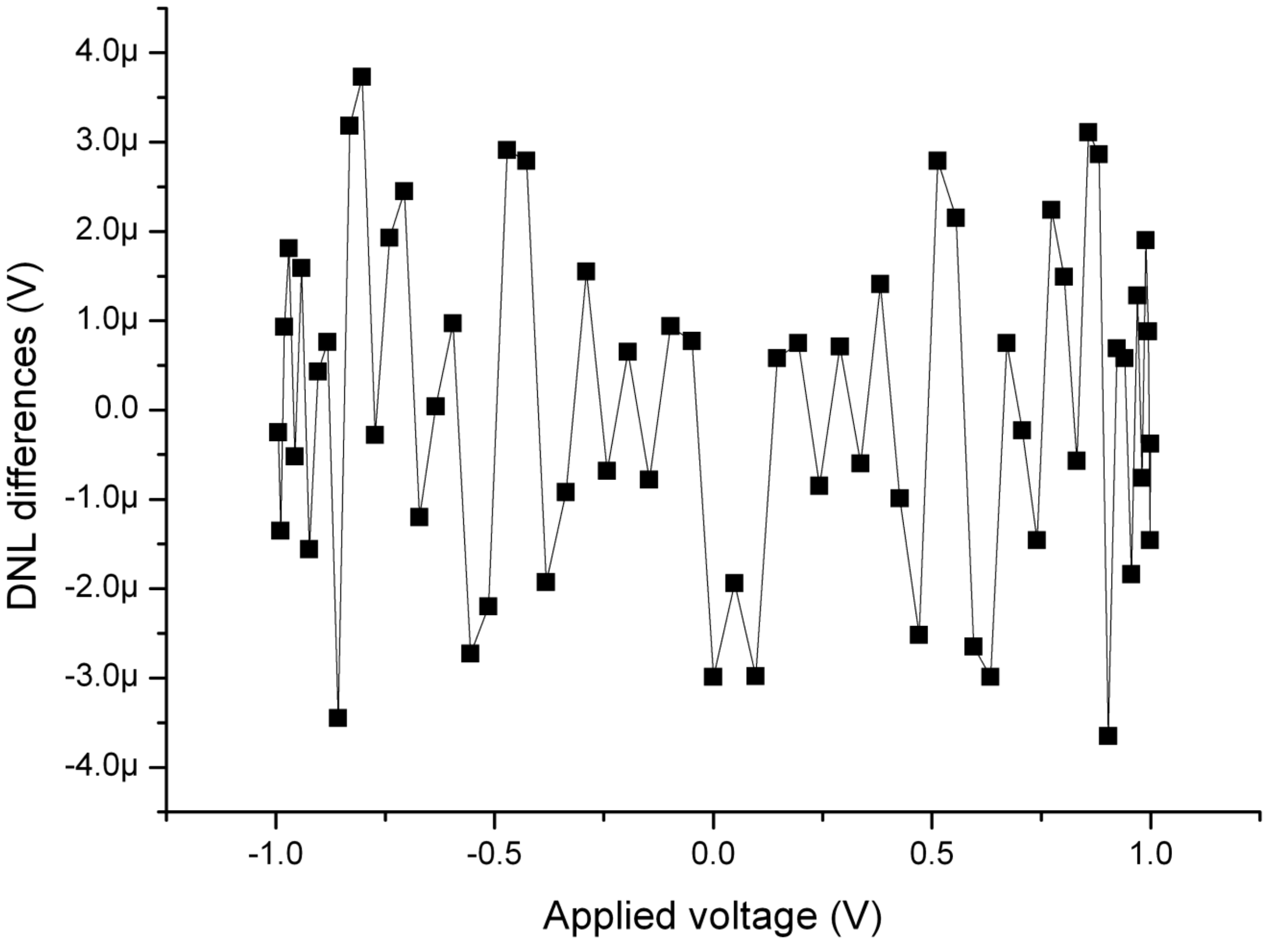
Settling time of voltmeter



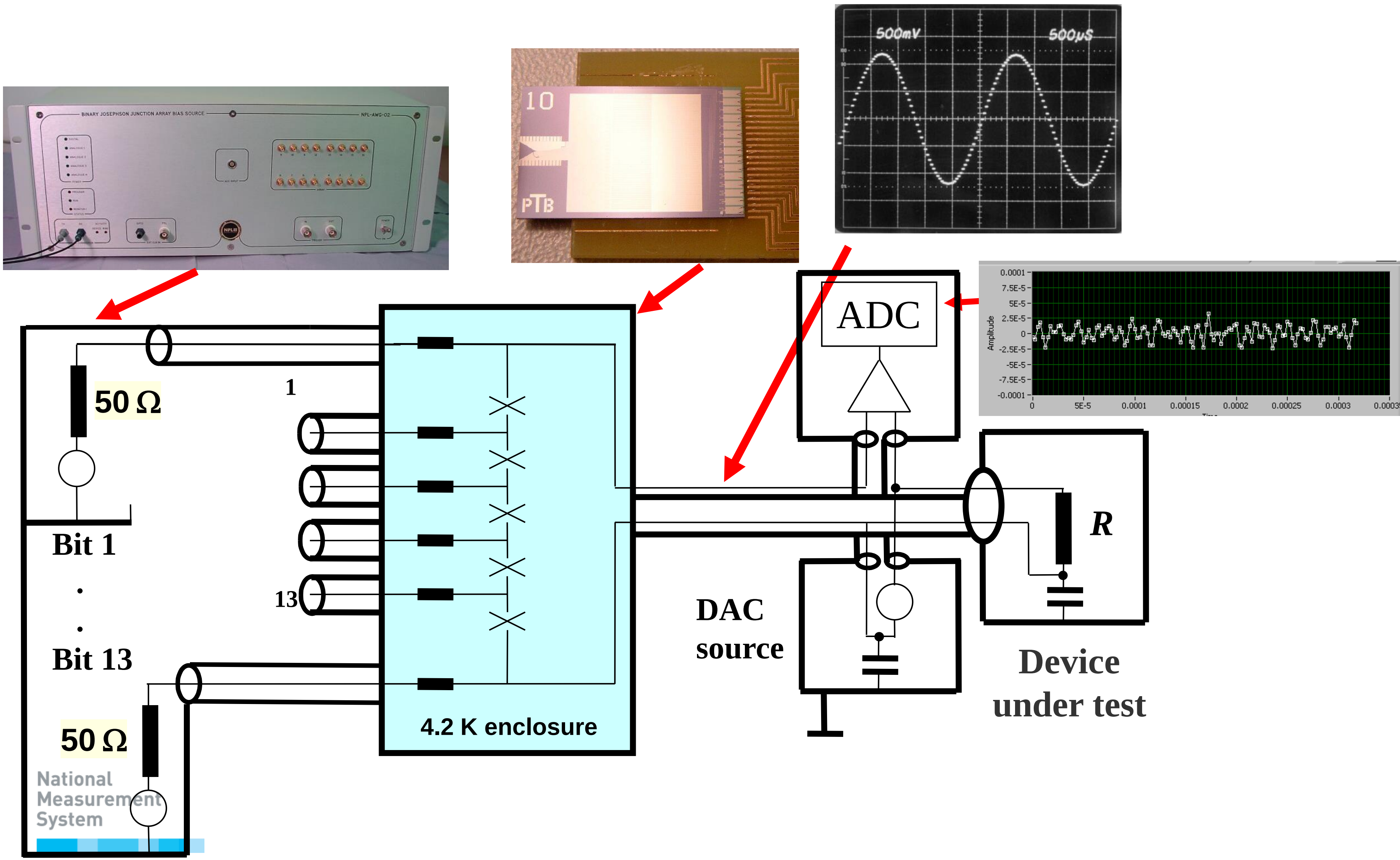
Henderson et al, *Measurement Science & Technology*, **23**, 124006, 2012

Differential non-linearity



Henderson et al, *Measurement Science & Technology*, **23**, 124006, 2012

Quantum reference and a voltage source



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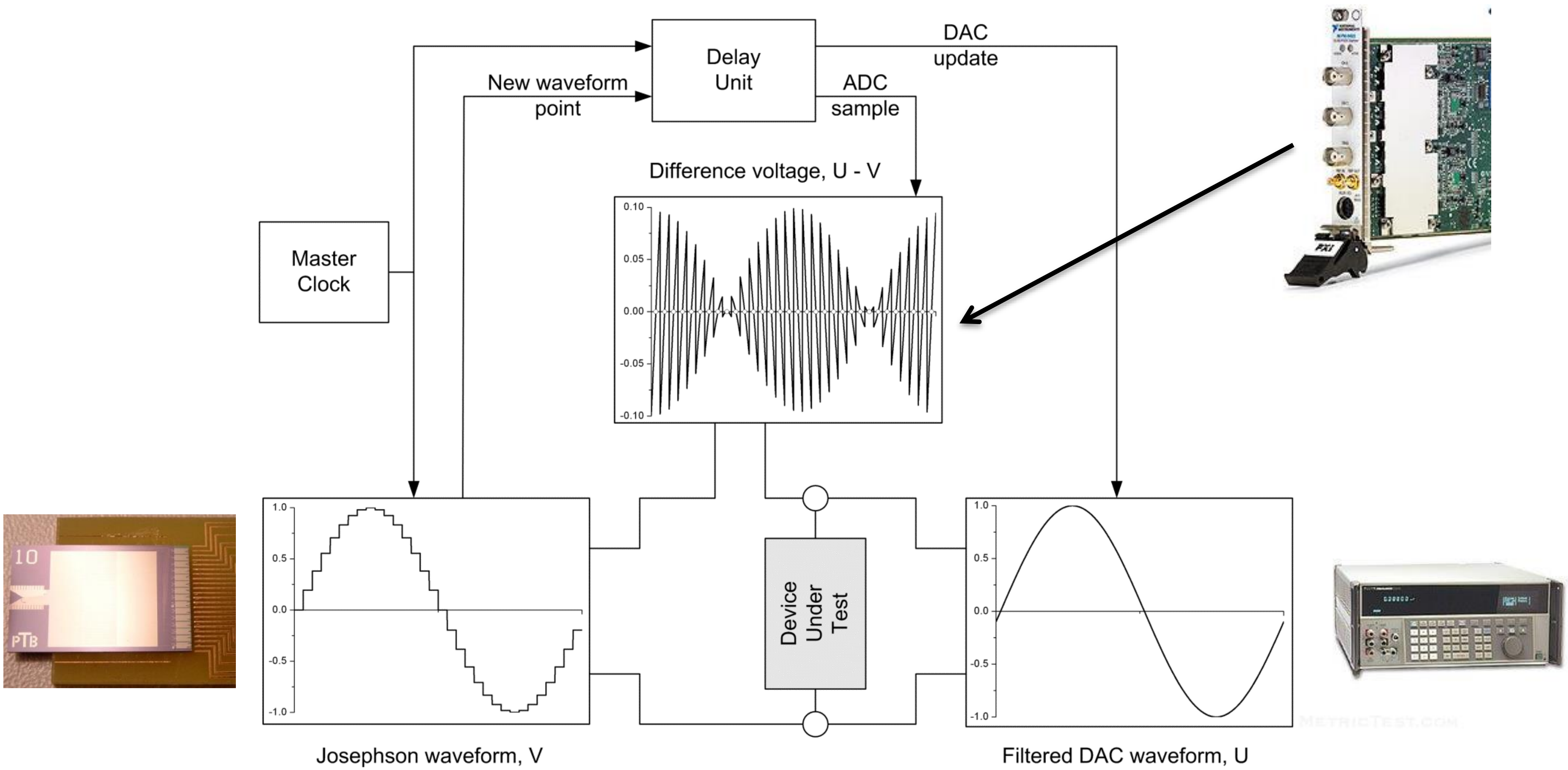
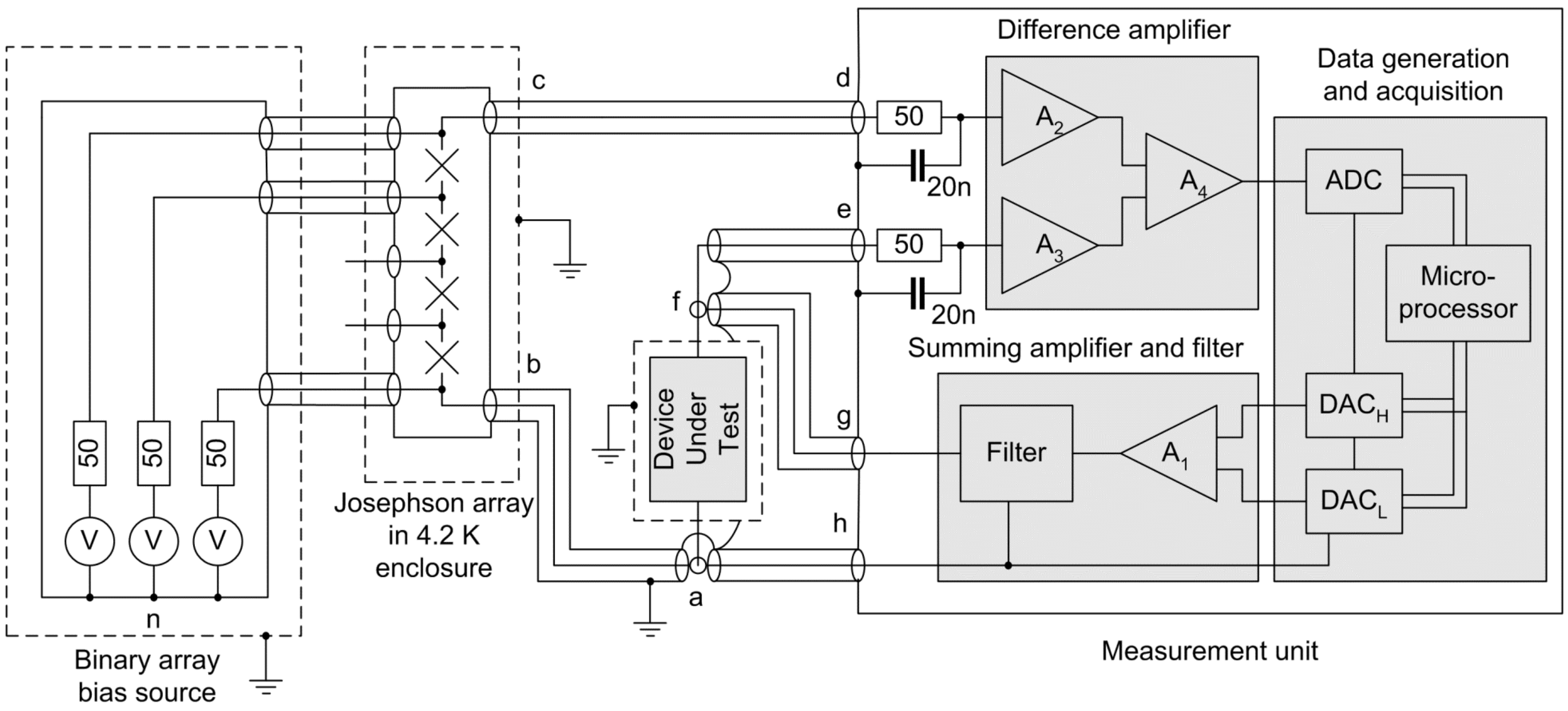
AC-Quantum voltmeter for sources employing a difference measurement



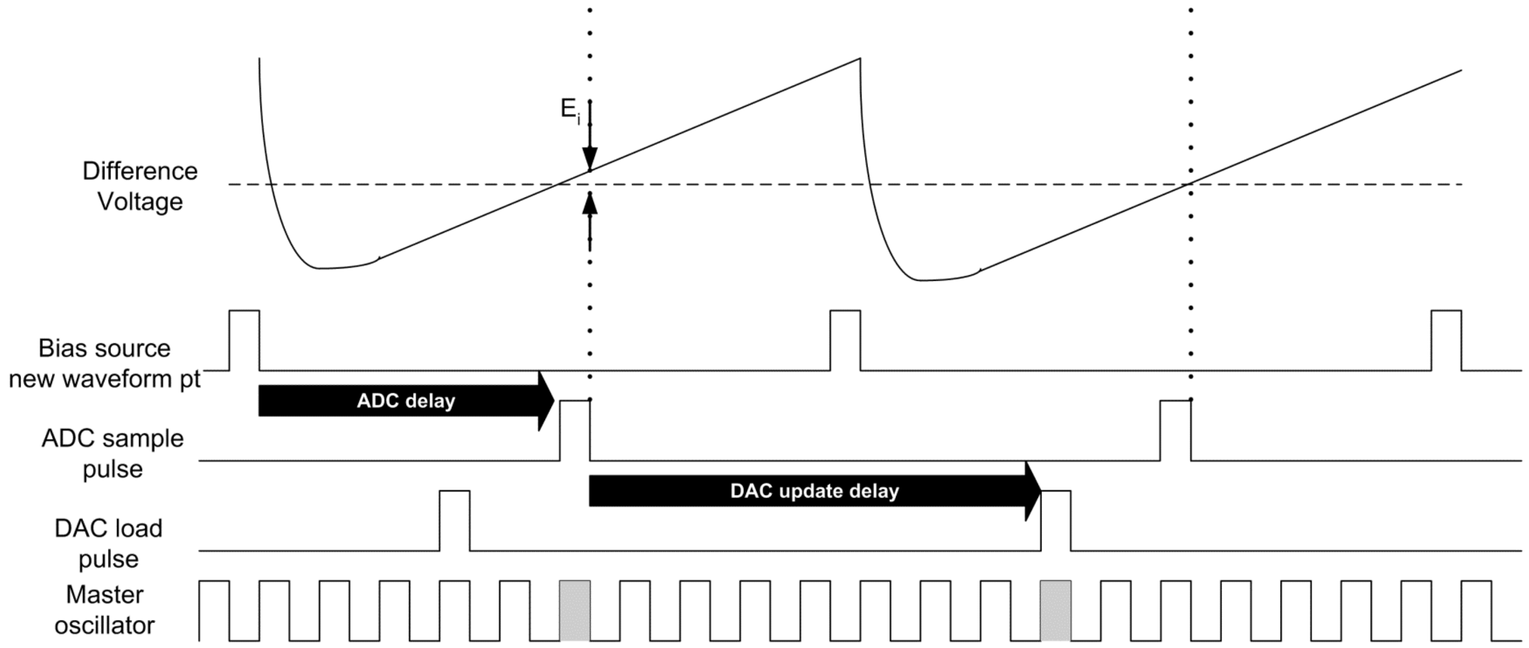
Lee et al, *Metrologia*, **50**, 612-622, 2013

Quantum-referenced waveform synthesizer



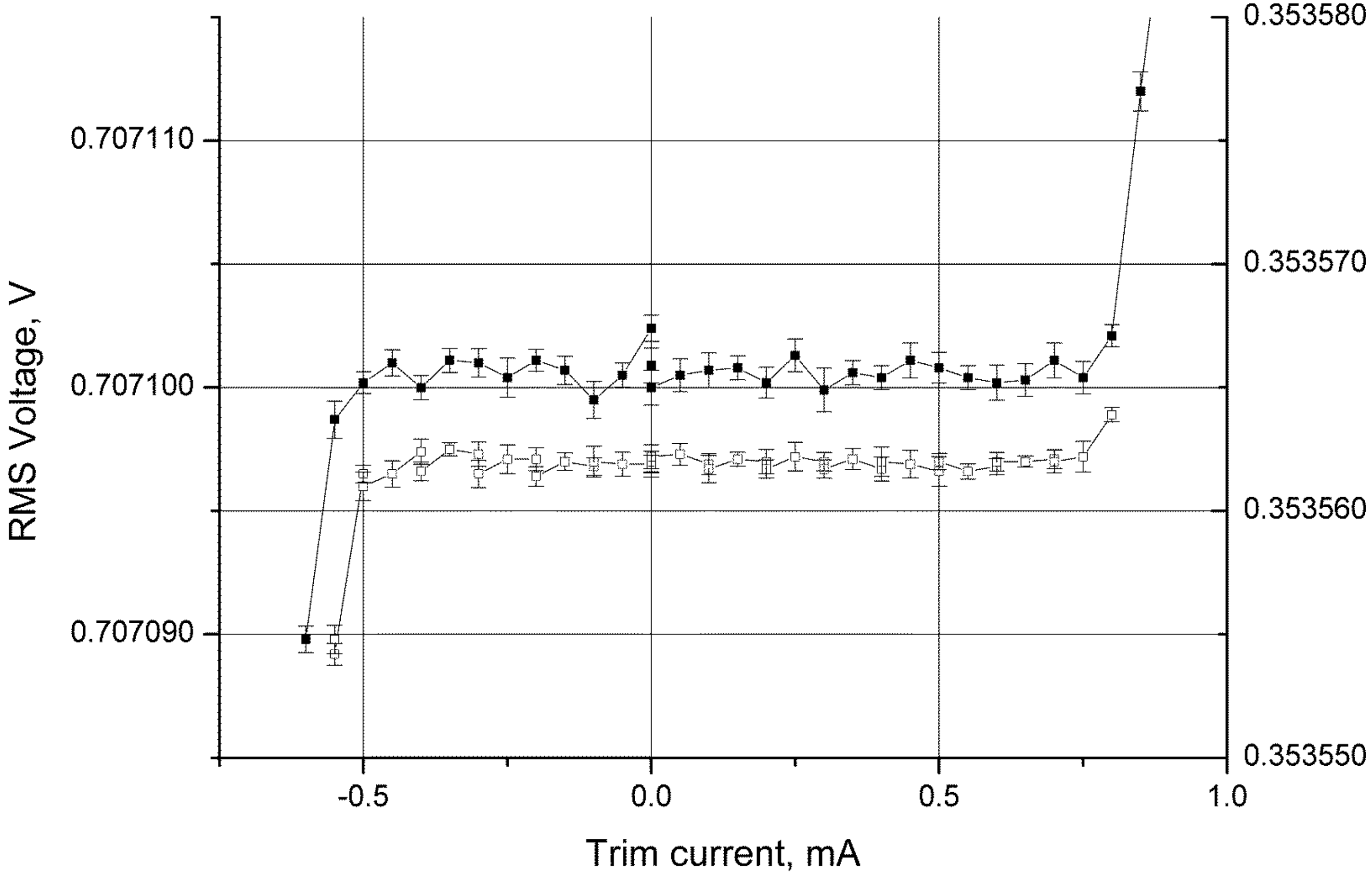
Williams et al, *IET Science Measurement & Technology*, **5**, 163-174, 2011

Data samples – one measurement per waveform update close to zero crossing of voltage difference



Williams et al, *IET Science Measurement & Technology*, **5**, 163-174, 2011

Josephson step flatness, measured using an RMS voltmeter



Williams et al, *IET Science Measurement & Technology*, **5**, 163-174, 2011

Summary

- What instrument is being measured?
- How is the measurement defined?
- How is the quantum standard realised?
- What is the effect of the connections?
- How is the measurement unce

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ACQ-PRO
Towards the propagation of AC Quantum Voltage Standards

Workshop on

quantum based voltage measurements

CRYOCOOLERS IN VOLTAGE METROLOGY*

** not only, actually*

22nd/26th June 2015
PTB, Braunschweig, Germany

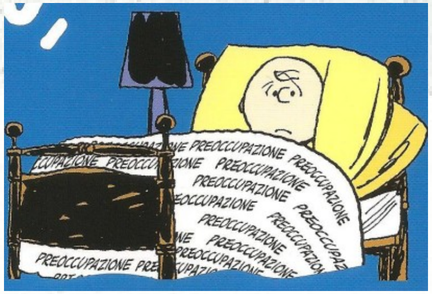
A. SOSSO - INRIM

Cryocoolers can be studied with different approaches

Ex: formal mathematical

WE'LL FOCUS ON PRACTICAL ISSUES

Very practical: why bother?



1) relief of the cryogenics-related pain

2) follows from 1: allow a wider number of people operate with cryo-devices (Sconductive in our case)

3) increased helium cost

4) rumors: helium will be unavailable sooner or later

Drawbacks of cryocoolers limited up to now application

Table 2. Potential problems with cryocoolers.

- Reliability
- Efficiency
- Size and weight
- Cooldown time
- Vibration
- Electromagnetic interference (EMI)
- Heat rejection
- Cost

+ thermal!

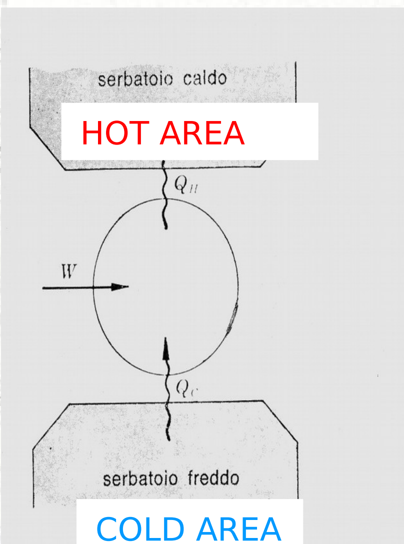
due to improvements, benefits are more and more outweighing disadvantages:

SPECIFIC TO AC Josephson: reduced length of cables!

So, what's all this cryocooler stuff anyhow?

Just a very special fridge.

Cooling can be obtained in by
1) **evaporation/boling**, enhanced e.g. by vapor pumping
2) **expansion** e.g. blowing a gas through an orifice



$$T_H > T_C$$

$$Q_H > Q_C$$

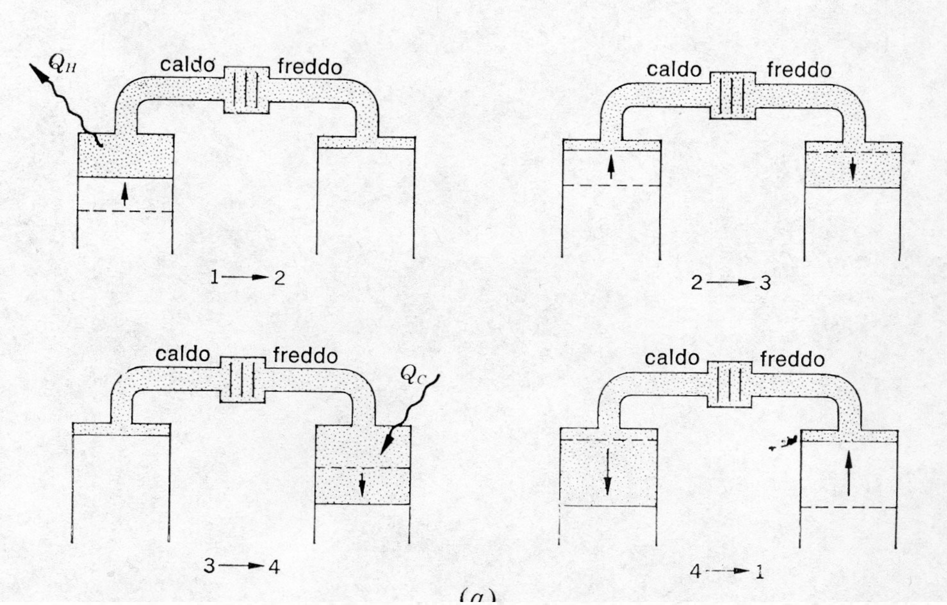
Thermodynamics says
we can't be 100% efficient:
extra heat is generated in the process

$$Q_H - Q_C = W$$

Inefficiency is related to the work we have to put into the process for transferring heat from high to low T!

The Stirling cooling cycle

90-15 K cryocoolers



(1→2) Left piston up,
heat out at high T

(2→3) Both piston move
(constant volume)
gas moves
to low T section

(3→4) cold piston moves
down, expansion
extracts heat in the
cold section

(4→1) Gas moves
back,cycle restarts

Joule-Kelvin(Thompson) cooler

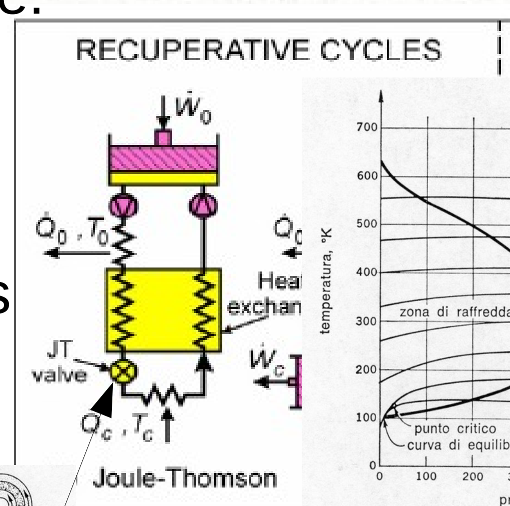
Uses expansion through an orifice:

- application to liquefiers

- scalable to small size

- rather complex thermodynamics

- constant pressure both sides of the orifice, but p1>p2



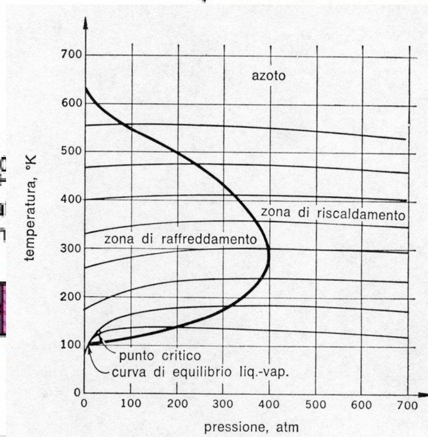


Fig. 12.2 Curve isoentalpiche e curva di inversione per l'azoto. (Da un diagramma T-S di F. Din, 1958.).

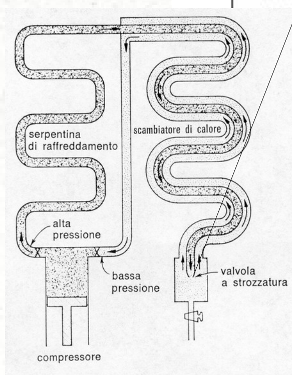


Fig. 12.5 Liquefazione di un gas per mezzo dell'effetto Joule-Kelvin.

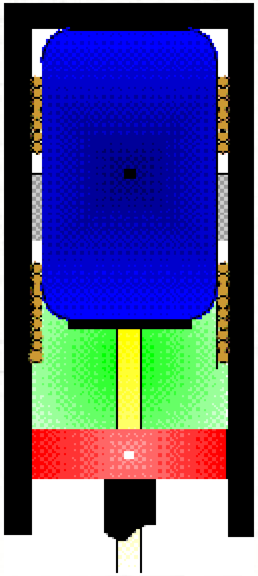
Pulsed flux coolers with regenerative exchangers

Non continuous/pulsed flux -> regenrative heat exchangers as temporary “cold storage” made with a porous material for maximum surface

- 70-80 K → steel, bronze, phosphorus, nickel
- down to 4 K → lead spheres+ rare earths (Nd, ErNi, $HoCu_2$, etc.)

Philips Stirling cooler

Single stage → 80 K (air liquefiers)
Two stages → down to a 4 K



Gifford-Mc Mahon Cryocoolers

Both single and multiple stages cicle requires external work ⇒ fig. 2.9

Different form Stirling gas flux from compressor is controlled by an **intake/exhaust valve** → vibrations reduced
→ BUT **displacer** piston in cooling volume
→ some noise → reduced reliability

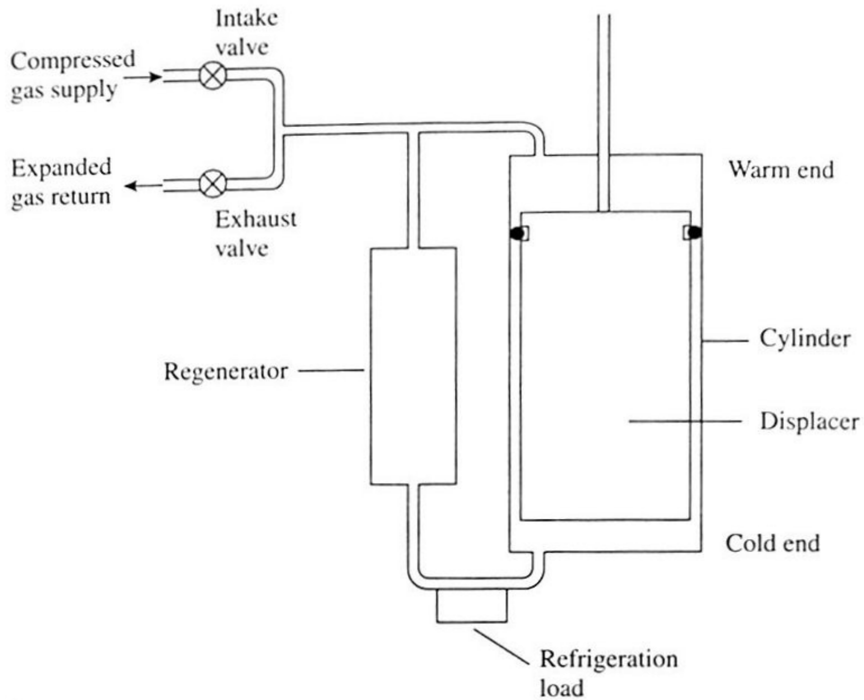


FIG. 2.9 A single-stage version of the Gifford–McMahon refrigerator (after McMahon 1960).

<u>Operation:</u>

I → *pressurize*
(intake open,
displacer down)

II → *intake*
(intake open,
displacer rising up)

III → *espansion*
(intake close,
exhaust slowly opening)

IV → *out*
(intake close, exhaust open,
displacer going down,
then exahaust closed)

Two/three stages for T < 4K

pulse tube cooling

Offrono le stesse prestazioni di refrigerazione dei Stirling e G-M ma viene eliminato il displacer e le vibrazioni associate

Le versioni più moderne (vedi fig. 2.10) hanno il moto del gas in fase con la pressione per mezzo di un orifizio e di un volume di riserva che immagazzina il gas durante mezzo ciclo e riduce le oscillazioni di pressione

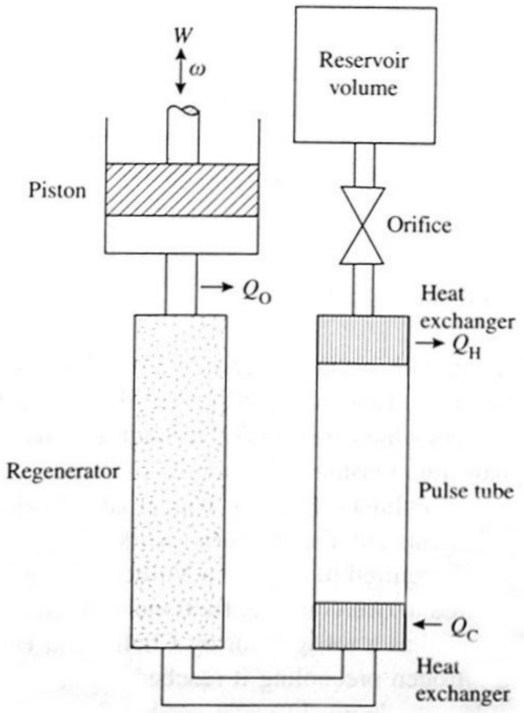


FIG. 2.10 Schematic diagram of an orifice pulse tube refrigerator (after Radebaugh 1990).

Fasi:

I → acoustic pressure wave
II → heat exchange of gas after orifice
gas compresso e riscaldato fluisce attraverso l'orifizio e scambia calore con lo scambiatore caldo
III → piston moves up -> gas espands adiabatically

IV → il gas raffreddato e a bassa p nel tube è forzato verso la parte fredda dal flusso che arriva dal serbatoio attraverso l'orifizio → passa attraverso lo scambiatore freddo e porta via calore

Il rigeneratore pre-riscalda il gas in ingresso ad alta pressione prima che raggiunga il lato freddo

Reservoir volume and orifice act like the GM displacer

The theory behind Pulse Tube Coolers is very similar to that of the Stirling Refrigerators, with the volume displacement mechanism of the displacer replaced by the orifice / surge volume configuration.

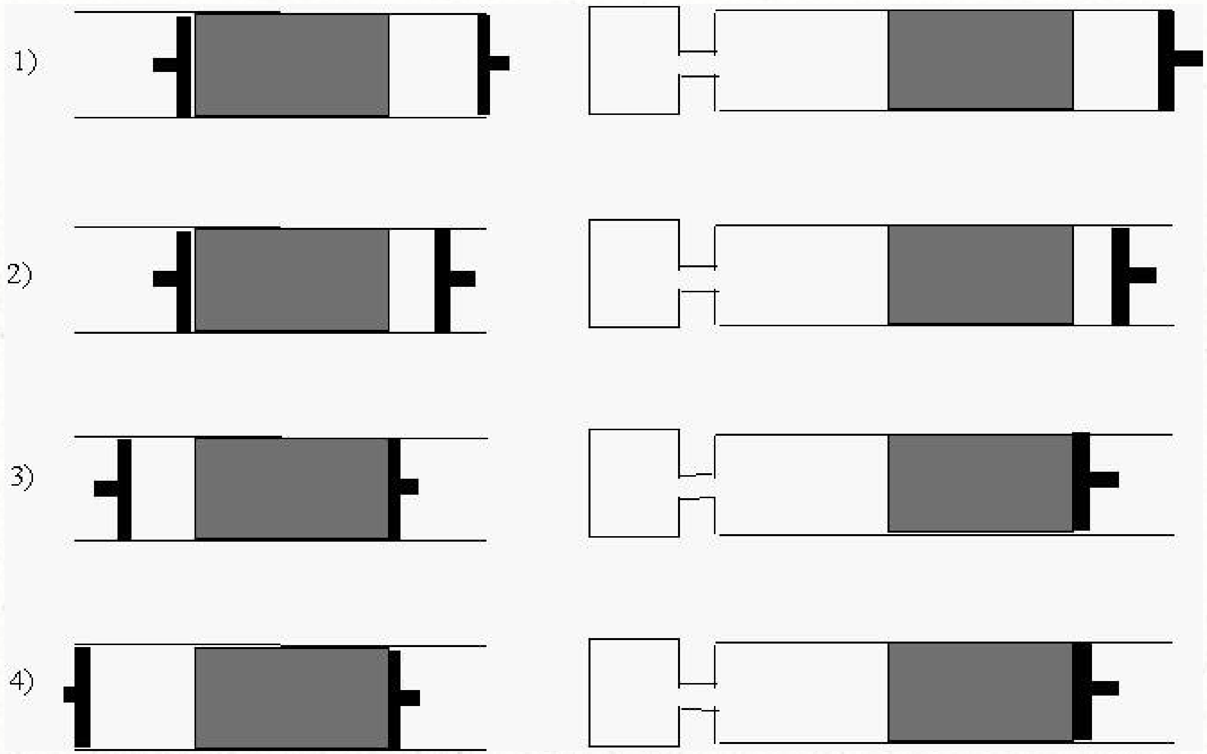


Figure shows the analog between the Stirling cooler and the pulse tube. As the compressor piston compresses from 1) to 2), the pressure in the system increases. During this phase, very little gas is transferred into the surge volume via the orifice, as the initial pressure difference across the orifice is small. As the piston compresses further from 2) to 3), more working gas passes through the orifice into the surge volume. The end result is very close to an isochoric process in a Stirling cycle (with the expansion of the displacer). The net effect is that the working gas is displaced across regenerator with heat transfer between the gas and the matrix material. As the compressor piston reaches its maximum stroke and becomes stationary 3) to 4), expansion occurs because gas continues to flow into the surge volume, which is at a lower pressure and the pressure within the pulse tube system drops. Finally, a combination of gas exiting the surge volume and the expansion of the compression space result in another near-isochoric process, 4) to 1) that completes the cycle. As a result, an amount of heat, QH=THdS is rejected from the system while QC=TCdS is absorbed at the coldtip.

PT403

CRYOMECH / PRODUCTS / CRYOREFRIGERATORS / PULSE TUBE CRYOREFR... / PT403

Supporting Documentation

PT403 Cryorefrigerator:

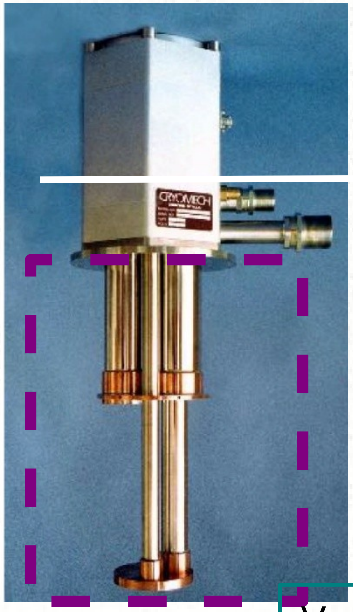
- Specification Sheet
- Capacity Curve
- System Drawing
- Cold Head Outline Drawing

PT403 Cryorefrigerator with Remote Motor Option:

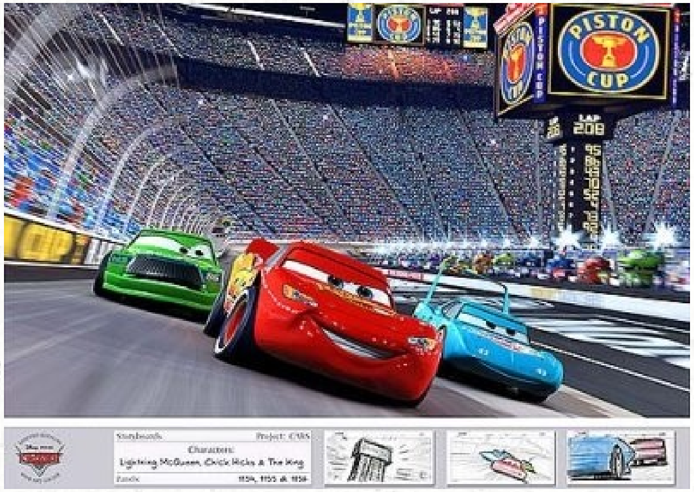
- Specification Sheet
- Capacity Curve
- System Drawing
- Cold Head Outline Drawing

Type	Two-Stage Pulse Tube Cryocooler
Cooling Capacity **2nd stage and 1st stage combined** ***Integrated motor version**	0.25W @ 4.2K with 7W @ 65K
Base Temperature	2.8K with no load
Cool Down Time	90 minutes to 4K
Helium Compressor Model	CP830 Air or Water Cooled
Available Electrical Options	200/230VAC; 1 Phase; 60Hz 200/220VAC; 1 Phase; 50Hz
Power Consumption (Input Power) **Water Cooled**	3.0kW @ 60Hz 3.0kW @ 50Hz
Power Consumption (Input Power) **Air Cooled**	3.2kW @ 60Hz 3.2kW @ 50Hz
Warranty	Three years or 12,000 hours (whichever comes first), on all parts and materials.
General Maintenance	First helium compressor maintenance cycle to be completed at 20,000 hours. Please contact Cryomech for Cold Head maintenance.
Available Options	Conflat/ISO Flange Bellows Assembly Remote Motor Condensing Heat Exchanger

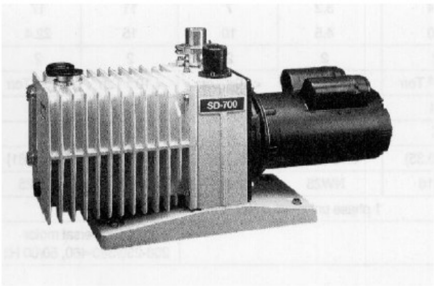
Cryocooler is just the "bare engine" not the end of the game!



Vacuum chamber

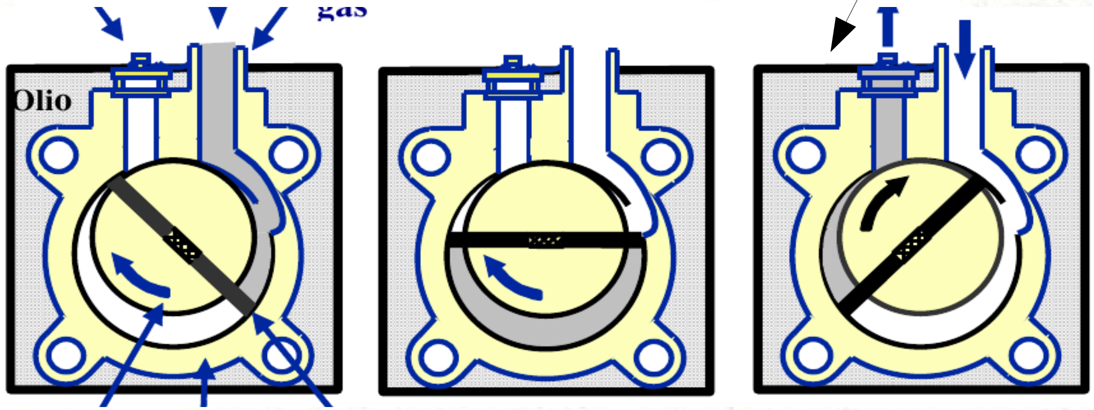


Vacuum first



Rotating vane pump

Roots pump



Issue: oil leakage from the pump entering the vacuum
→ Dry pumps

Min pressure ~ 10^{-2}

Quite good vacuum needed

To reach the 10^{-4} mbar pressure required for cryocooler operation a **turbo-molecular** pump is typically needed.

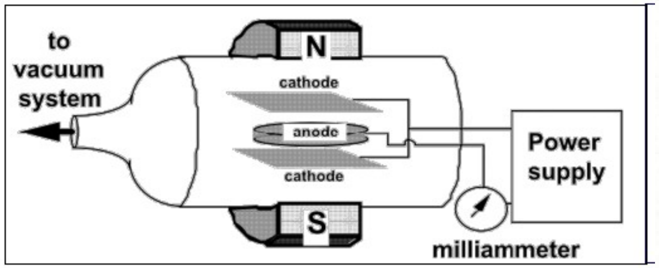
Turbo pumps can be easily damaged: it's preferable to start with a mechanical pump (ex. down to 10^{-2}) . So you'll need both for your cryocooler.

Cryocooler "cryo-pumps" when temperature drops: pressure goes to very low levels during operation.

Needless to say?
To measure is to know

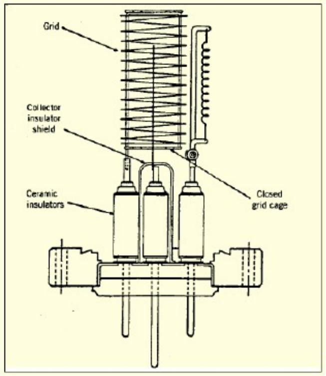
Low Pressure Measurements

widely used techniques are



Cold-cathode gauge (Pennig)

Very robust and common, but BEWARE the strong magnet! S.Conductors may not like it.



Hot-cathode gauge

Thermo-ionic effect, 1000 C filament, measures ionic current, range 10^{-1}-1^{-10}, shorter life

yet another measurement..
how cool are we?

In cryogenics the most used technique to measure temperature (above 50 mK) is

Resistance thermometry

- Different types:

a) **Pure metallic elements** (Pt, Au, Cu)

b) **Semiconductors** with resistance increasing as T decrease [Ge, Si,RuO_2]

→ high sensitivity

c) **Metallic alloys** with magnetic materials [RhFe, PtCo] → NO, THANKS

“d”) **diodes** (not resistance but volt-amperomentric, anyway)

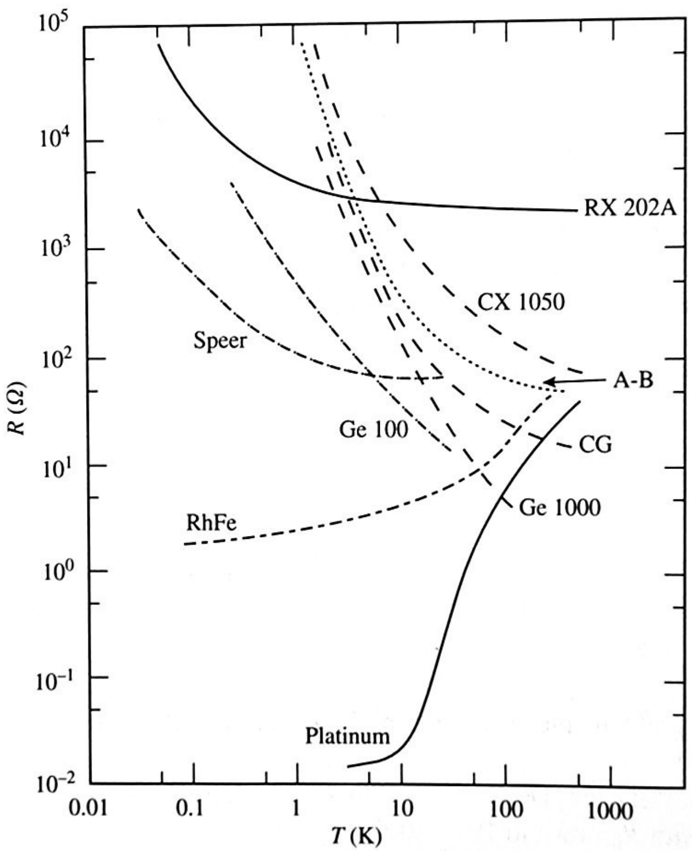
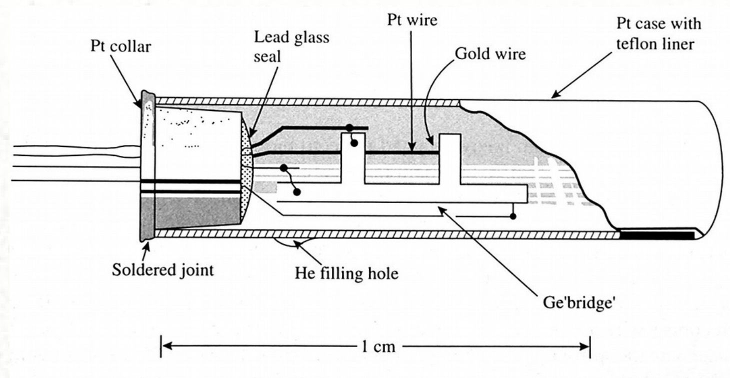


FIG. 3.7 The electrical resistance $R(T)$ of some typical thermometers. A-B denotes Allen-Bradley carbon resistor. Speer is a carbon resistor. CG is carbon-in-glass. CX 1050 is a Cernox and RX 202A is a ruthenium oxide from LakeShore. Ge 100 and Ge 1000 are Cryocal germanium thermometers.

Semiconductors

Germanium (p or n) doped

Below 100 K only holes or dopant electrons.
Range 0.3-40 K.
→ stable with thermal cycling ($\Delta T \sim 1$ mK)



3.9 Encapsulated germanium thermometer (after Kunzler *et al.* 1957).

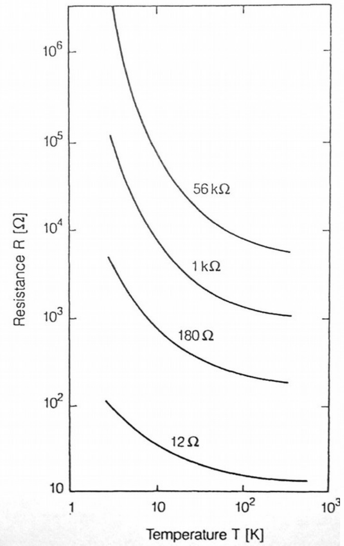


Fig. 12.11. Temperature dependence of the resistances of four Allen-Bradley carbon resistors (1/8W) with the indicated room-temperature resistances [12.10]

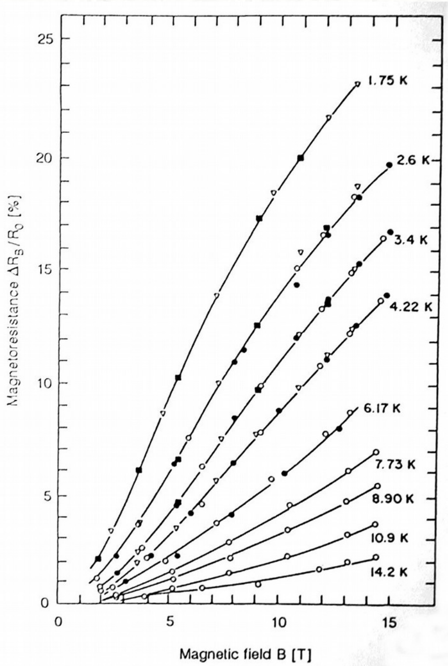


Fig. 12.17. Magnetoresistances of 47 Ω, 1/4 W Allen-Bradley carbon thermometers [12.37]

Carbon resistors

- Originally made for electronics
- Very cheap

Allen-Bradley: 1/8 W
small
cheap
T >1 K;

Matsushita: T > 10 mK

Speer: down to 10 mK

Resistors

Thick film RuO_2 (SMD)

RuO_2 + (PbO-B_2O_3-SiO_2) “glass” on alumina → accurately fittted

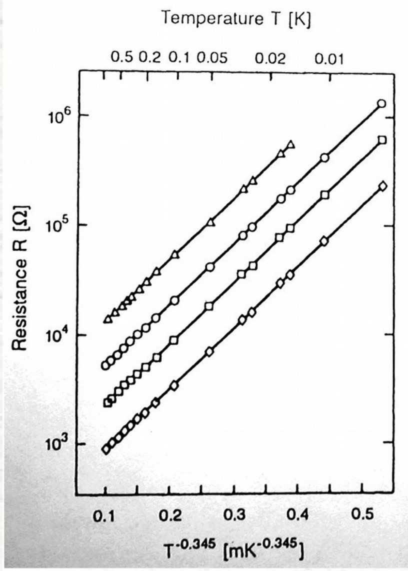


Fig. 12.22. Resistances versus $T^{-0.345}$ of four different RuO_2 resistors with approximate room temperature values of 0.5 kΩ (◇), 1 kΩ (□), 2 kΩ (○), and 4.7 kΩ (Δ), respectively. The upper horizontal scale shows the temperature in Kelvin [12.60]

cheap
very small
highly repeatable
small thermal capacitance

Cernox

0.3 - 300 K

Diodes

10 μA constant current → p-n junction voltage. Ok down to 1 K (with proper calibration)

Table 3.9 Summary of secondary temperature sensors for $T \leq 300$ K

Type	Range (K)	Sensitivity (mK)	Stability (mK)	$\Delta T/T$ (%) 2.5 T @ 4.2 K	$\Delta T/T$ (%) 2.5 T@10 K
Pt (PRT) (encaps)	>12	1	1	NA	100*
Pt (film)	>12	1–10	<100	NA	100*
RhFe (encaps)	0.5–300	1	1	11	6
RhFe (chip)	0.5–300	±10	±20	10	—
Carbon (A-B) (47, 100, 220 Ω)	0.5–100	1–10	<100	<1	<1
Carbon (Speer) (100, 220, 470 Ω)	0.5–300	1–10	<100	4–9	
Carbon-glass	1–300	1-10	5 (4.2 K) 30 (15 K)	0.5	0.2
Ge (GRT)	0.5–30	1	1–10	5–20*	4–15*
Cernox	0.3–300	±3	±20	<1	
Rox	0.02–200	10	±20	<1	
p-n junction(Si)	1–300	10	50	~100*	<50*
p-n junction(GaAlAs)	1–300	10	50	2–3*	1–2*
Capacitor ($SrTiO_3$)	0.5–60		≤500	→ 0	
Thermocouples					
Cu vs constantan	10–300	100 (>20 K)	100	see Section 3.8	
AuFe vs chromel	1–300	10 (10 K)	—	—	3

The values given are rough averages taken from more extensive sources (e.g. Quinn 1990; *LakeShore catalogue of temperature measurement and control* 1995). Errors in T induced by a magnetic field of 2.5 T may be strongly dependent on orientation (see those marked with ∗). A-B denotes Allen-Bradley.

International Temperature Scale ITS-90

Table 3.1 Defining fixed points of ITS-90 with estimates of their uncertainty ΔT (Quinn 1990; Preston-Thomas 1990)

Fixed points	T_{90} (K)	ΔT (mK)
$^4He/^3He$ vap. press.	3–5	
e-H_2 t.p.	13.8033	0.5
Ne t.p.	24.5561	0.5
O_2 t.p.	54.3584	1
Ar t.p.	83.8058	1.5
Hg t.p.	234.3156	1.5
Water t.p.	273.16	0
Ga m.p.	302.9146	1
In f.p.	429.7485	3
At higher temps Sn, Zn, Al, etc. (m.p. and f.p. at pressure of 101 325 Pa)		
Superconductor	**T_c (K)**	**Width (mK)**
W	0.016	0.7
Be	0.023	0.2
Ir	0.099	0.8
$AuAl_2$	0.1605	0.3
$AuIn_2$	0.2065	0.4
Cd	0.5190	0.5–0.8
Zn	0.8510	2.5–10
Al	1.1796	1.5–4
In	3.4145	0.5–2.5
Pb	7.1996	0.6–2

The lower section shows some superconducting transition temperatures, T_c (with width of transition), for metals encapsulated in SRM 767 and SRM 768 (Quinn 1990, p. 183).

- Tra 0.65 e 5 K → te sione di vapore di He^3 e He^4
- Tra 3 K e pur Ne (24.55 K) → termometro
- Tra pur e 961.78 °C → term o calib
- di He^3 e He^4

$$A_i \left[\frac{\ln p - B}{C}\right]^i$$

=1

m vapour

CALIBRATION NEEDED?

			He 2.1768–5.0 K
A_0		8	3.146631
A_1		153	1.357655
A_2	0	166756	0.413923
A_3	0.3	0.050988	0.091159
A_4	0.1516	0.026514	0.016349
A_5	−0.002263	0.001975	0.001826
A_6	0.006596	−0.017976	−0.004325
A_7	0.088966	0.005409	−0.004973
A_8	−0.004770	0.013259	0
A_9	−0.054943	0	0
B	7.3	5.6	10.3
C	4.3	2.9	1.9

Take control over T

Knowing temperature is not sufficient, It must be finely controlled.

Cryocooler is always at work to reduce T: to control it an resistive heating element is needed.

For optimal performances you have to find best:

Proportional

Integral

(and in few cases) **D**erivative

coefficients of your control loop

Cryocooler requires careful thermal design

uniform chip operation --> control of thermal gradients

low cooling power --> minimize thermal links

***Issues*: coax/microwave guide heat load**

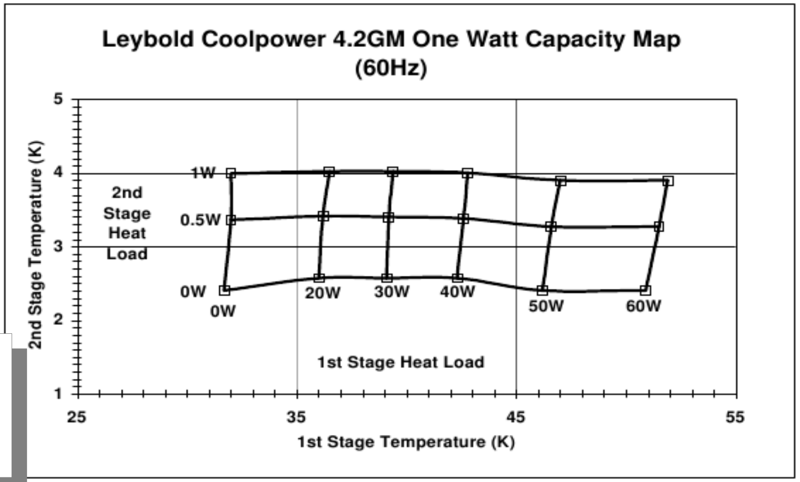
▼

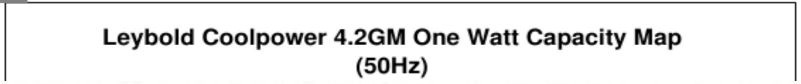
Thermal anchoring to 1st stage reduces temperature difference to second stage

Radiation shields around low temperature volumes reduces heat from radiated power

Always try to move the thermal load to 1st stage
- 1st stage can withstand a much higher load
- loading 1st stage may even be beneficial

Coolpower 4.2 *One Watt* Performance Data





Thermal contact & insulation

Owing to the low pressure, thermal conduction:

- **thrugh solids**
- **irradiation**

Table 4.1 Mean values of thermal conductivity (in $W\,m^{-1}\,K^{-1}$)

Material	$\bar{\lambda}$ $T_2 = 300\,K$ $T_1 = 77\,K$	$\bar{\lambda}$ $T_2 = 300\,K$ $T_1 = 4\,K$	$\bar{\lambda}$ $T_2 = 77\,K$ $T_1 = 4\,K$	$\bar{\lambda}$ $T_2 = 4\,K$ $T_1 = 1\,K$	$\bar{\lambda}$ $T_2 = 1\,K$ $T_1 = 0.1\,K$
Copper (electrolytic)	410	570	980	200	(40)
Copper (phos-deoxid.)	190	160	80	5	(1)
Brass (70Cu/30Zn)	81	67	26	1.7	0.35
Constantan (60Cu/40Ni)	20	18	14	0.4	0.05
Inconel X	10.7	8.9	4.6	—	—
18/8 st. steel	12.3	10.3	4.3	0.2	0.06
MGC	2	1.6	1.3	0.03	0.004
Pyrex	0.82	0.68	0.25	0.06	0.006
Nylon	0.31	0.27	0.17	0.006	0.001

Thermal conductance is temperature dependent

$$\dot{Q} = \bar{\kappa} \frac{A}{l} \Delta T$$

$$\bar{\kappa} = \frac{1}{T_1 - T_2} \int_{T_1}^{T_2} \kappa(T)\, dT$$

4.6 Selezione dei materiali

A seguito di quello che abbiamo detto in precedenza si conclude che:

Per una **buona conducibilità termica** le scelte giuste sono Cu (ma: morbido, calore specifico nucleare a T < 1 K), Ag (ma: morbido, costoso) oppure Al (ma: morbido, superconduttore sotto a 1 K, difficoltà di saldatura).

Per **l'isolamento termico** le scelte giuste sono le plastiche (Teflon, Nylon, PMMA, eccetera), la grafite (attenzione: ne esistono di diverse varietà), l'allumina, tubi a parete sottile di acciaio inossidabile (ma la saldatura non è semplice) o di cupro-nichel (più facili da saldare). In generale i vetri o i materiali composti da piccoli cristalli e che contengono una grossa quantità di difetti e impurità sono dei buoni isolanti termici.
Se le altre proprietà non hanno molta importanza, le leghe di alluminio oppure l'ottone possono essere usati in virtù del loro costo relativamente basso e della loro facile lavorabilità.

Per quanto riguarda **i fili** che portano i segnali elettrici da temperatura ambiente alle basse temperature criogeniche abbiamo già detto. Per terminali di bassa corrente, fili sottili di costantana o di manganina sono i migliori per la loro bassa conducibilità termica e per la piccola dipendenza dalla temperatura della loro proprietà elettriche. Se grandi correnti elettriche devono essere trasportate (come quelle per alimentare i magneti superconduttori) si finisce quasi sempre di scegliere i cavi in rame a patto di collegarli attentamente con pozzi di calore durante il loro percorso per andare alle basse temperature. A T< 1 K la scelta migliore è l'uso di fili superconduttori che possono esser ottenuti ricoprendo di saldante superconduttore dei sottili fili di manganina o di costantana.

I fili per la **misura di piccoli segnali** devono, naturalmente, essere sempre arrotolati su se stessi, fissati rigidamente e ben schermati per ridurre i rumori elettrici dall'esterno.

4.8 Resistenza termica di contatto (Kapitza)

4.8.1 Resistenza di contatto tra metalli

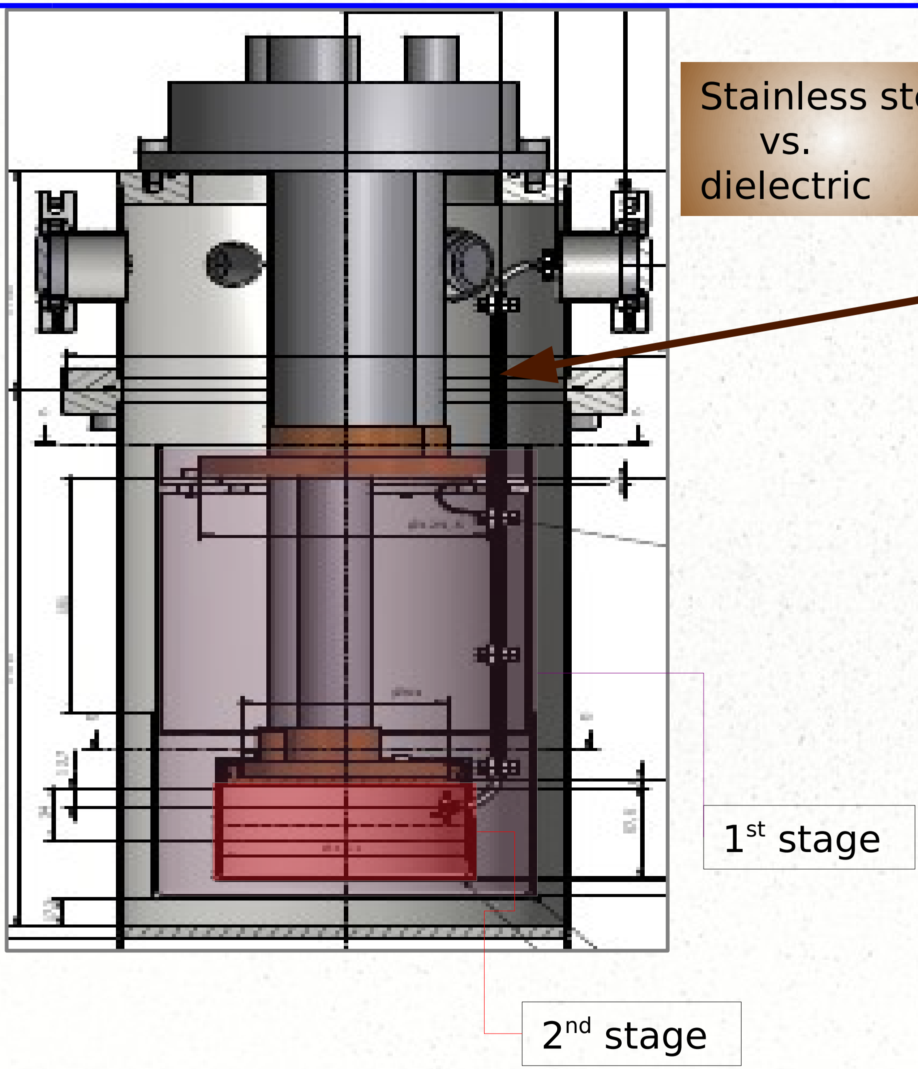
Raggiungere l'equilibrio termico in un sistema diventa via via sempre più difficile quando la temperatura è abbassata non solo perché la conducibilità termica dei materiali diminuisce, ma anche perché compare una **resistenza termica di contatto** all'interfaccia tra due materiali che diventa via via più grande all'abbassarsi della temperatura.
Questa resistenza produce un salto termico alle interfacce tra i materiali dato da:

$$\Delta T = R_K \dot{Q}$$

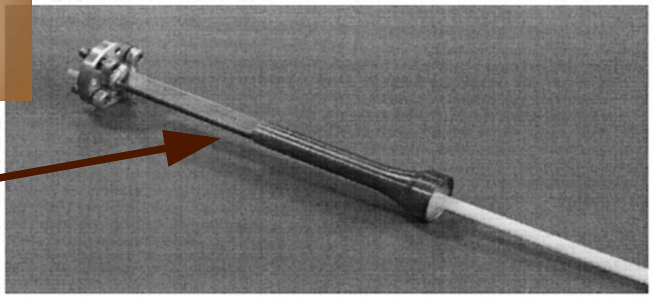
Dove R_K è la resistenza termica di contatto o **resistenza di Kapitza**. Le resistenze di contatto tra diversi tipi di materiali e tra i materiali e i fluidi criogenici sono mostrate in figura 4.5.

Siccome, in prima approssimazione, R_K è inversamente proporzionale all'area effettiva del contatto, e siccome quest'area è soltanto circa 10^{-6} dell'area di contatto apparente a causa delle microscopiche irregolarità delle superfici metalliche affacciate, la resistenza di contatto può essere ridotta notevolmente applicando un'intensa pressione tra le superfici.

SETTING UP YOUR OWN



Stainless steel
vs.
dielectric



COLDHEAD VESTING:

vacuum chamber

feedthough

shields

Cryocooler is just the “engine“ **not the end of the game**

COLDPLATE DESIGN:

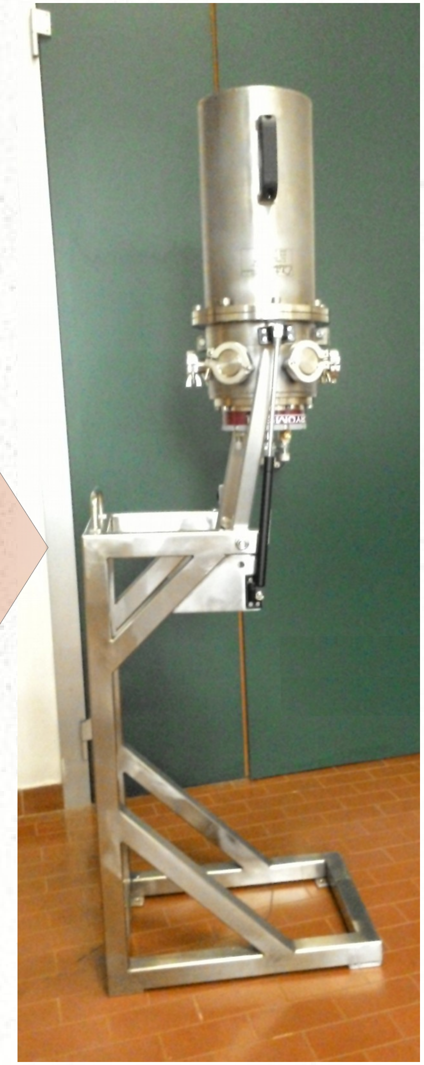
Thermometer(s)
Heater for temperature control
signal wires
Thermal contact

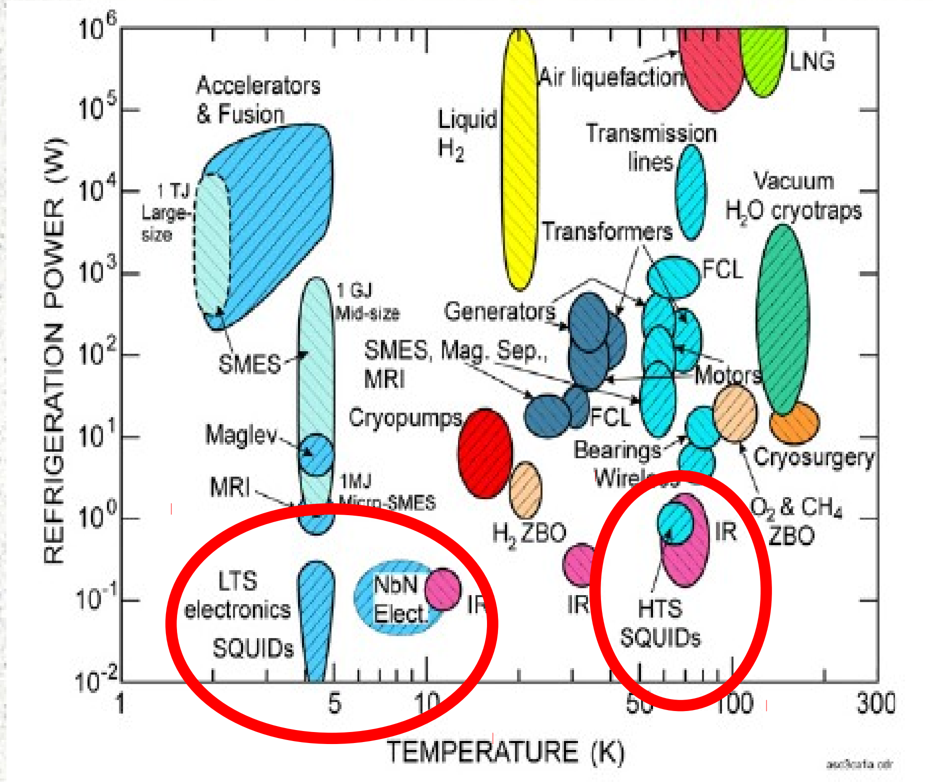
If you're planning to go for a Pulse-Tube (the standard way, at present)

one pulse tube nuisance

Pulse tube coolers must **work upside down**

..and the solution we chose: *tilting support*





- G.K. White and P.J. Meeson, Experimental Techniques in Low-Temperature Physics, Oxford Science Publications, Clarendon, 2002
- F. Pobell, Matter and Methods at Low Temperatures, Springer, 1996
- Ray Radebaugh: Cryocoolers: the state of the art and recent developments, J. Phys.: Condens. Matter 21 (2009)

THANK YOU FOR YOUR ATTENTION

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Using a JAWS system inside a cryocooler

Technical basics

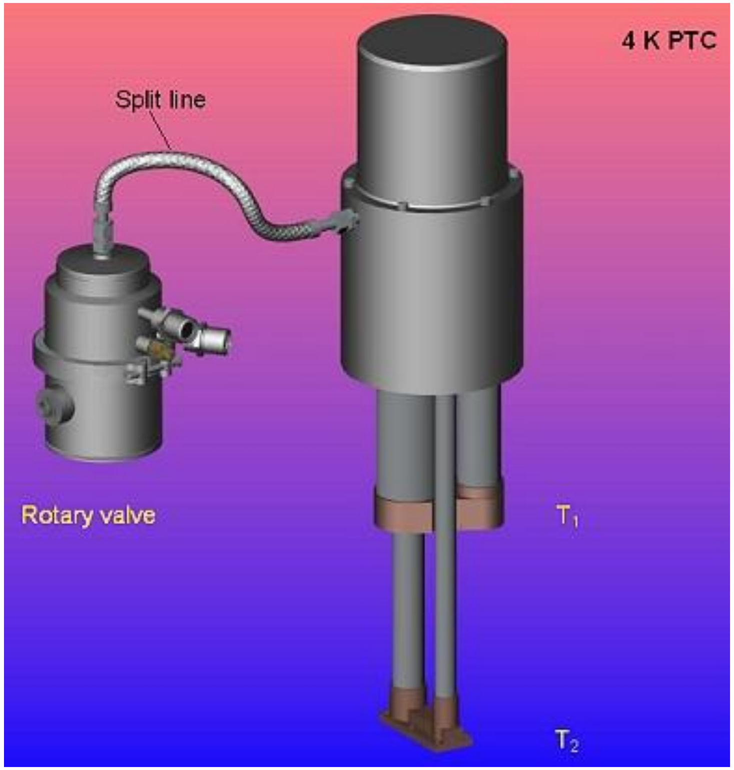
S. Bauer, R. Behr, T. Hagen, O. Kieler, J. Lee, T. Möhring and L. Palafox

Pulse-Tube Cryocooler

Pulse-Tube cryocooler

- Pulse-tube coolers are working without moving parts at the cold side in contrast to Sterling or classical Gifford-McMahon cryocoolers
    - more compact design of cold head
    - less vibrations
- Rotary valve connects high and low pressure side of the compressor unit to PTC
- Pulse-tube = Thin-walled cylinder filled with porous material of high heat capacity (e.g. rare earths)
- The coolant (Helium gas) takes and carry away heat by the periodic compression and expansion
- PTC is more reliable compared to those coolers with moving ports
- No LHe logistic needed
- Maintenance is needed every 30.000 h of operation for the compressor unit

Pulse-Tube cryocooler



Picture: TransMIT (http://cryo.transmit.de)

Required infrastructure

Required infrastructure

- Infrastructure for compressor unit
  - Cooling water for compressor unit:
    - Flow rate: **6-10 L/min** (more if ethylene glycol is added)
    - Temperature of cooling water: **5 to 25°C** depending on flow rate
    - Air cooled (wall mounted -> outside) unit also available
  - 380 V3~ (50 Hz) or 480 V3~ (60Hz) for compressor unit (approx. 9 kW)
    - Low voltage models also available
  - Sound absorption for compressor unit:
    - Operation in a sound absorbing box (PTB)
    - Operation in a dedicated room or outside the building
  - Vacuum system (<10^{-5} mbar)
    - Turbo molecular pump (TMP) and backing pump

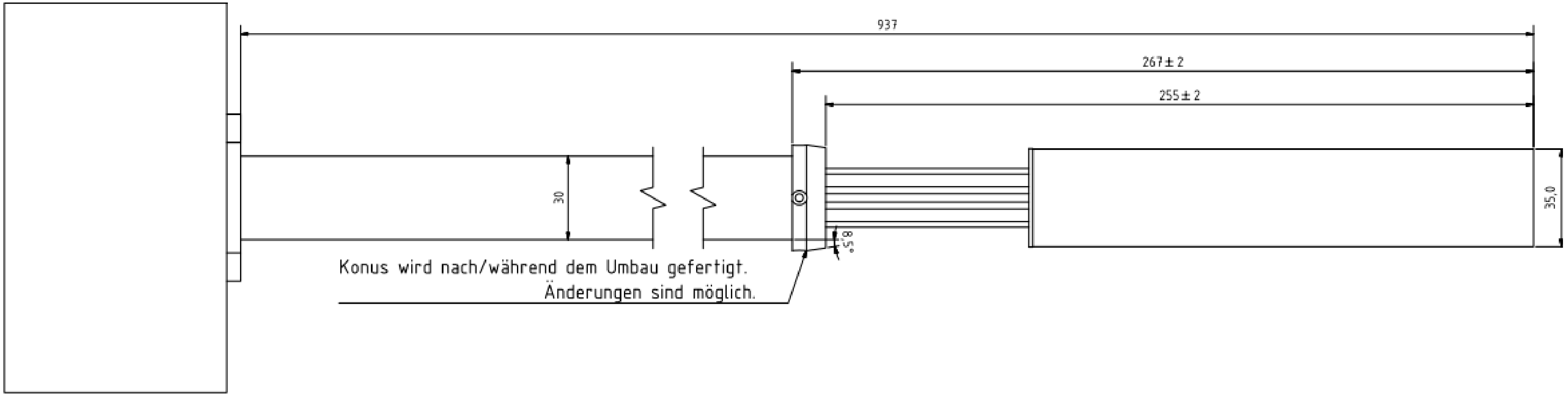
Sample mounting and Cryoprobe design

Sample mounting

- In principle two possibilities to install sample:
  - Sample fixed to 2nd stage of PTC
    - Best solution for ideal cooling
    - Short cables
    - Less flexible
  - Sample mounted in cryoprobe (top-loading system)
    - Reduced heat transfer due to exchange gas
    - Long cables > 1 m
    - Fast change of sample (~1h) and hence good for testing and multipurpose use

Cryoprobe design

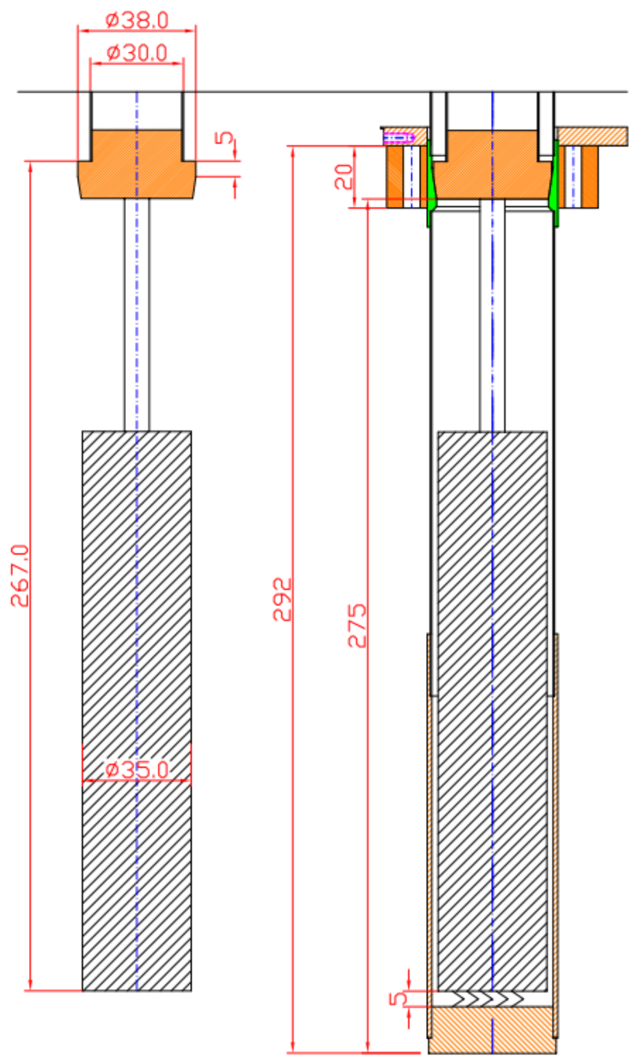
- Particular attention must be paid to the thermal conduction of the materials used
  - Main part is a thin walled stainless steel tube
  - HF lines have to be suitable for low temperature (e.g. outer conductor stainless steel / inner conductor CuBe)
  - LF Connection leads made from thin copper wires or small coaxial cables



Cryoprobe design

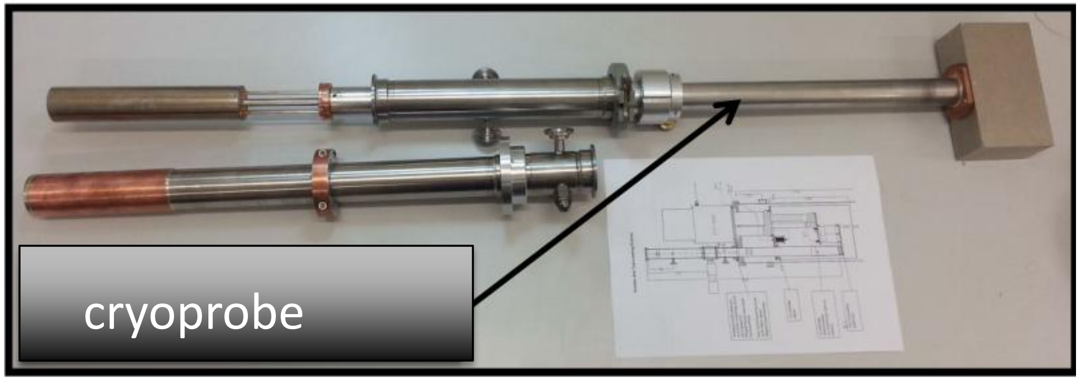
- In order to reduce the heat load to the 2nd stage we connected the stainless steel tube to the 1st stage via a copper cone
- The cryoperm cup is connected to the bottom of the top-loading tube via a mesh of copper wool
- Regarding all this design criteria the PTB system has a heat transfer to the second stage of about:

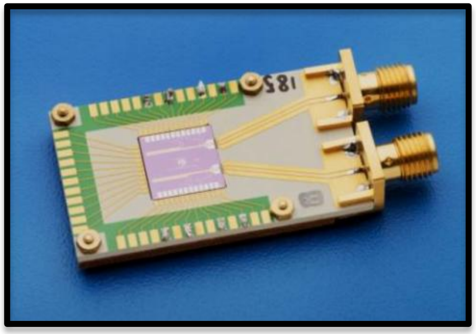
$$\dot{Q} \approx 100\,\mathrm{mW}$$



TransMIT Cryocooler

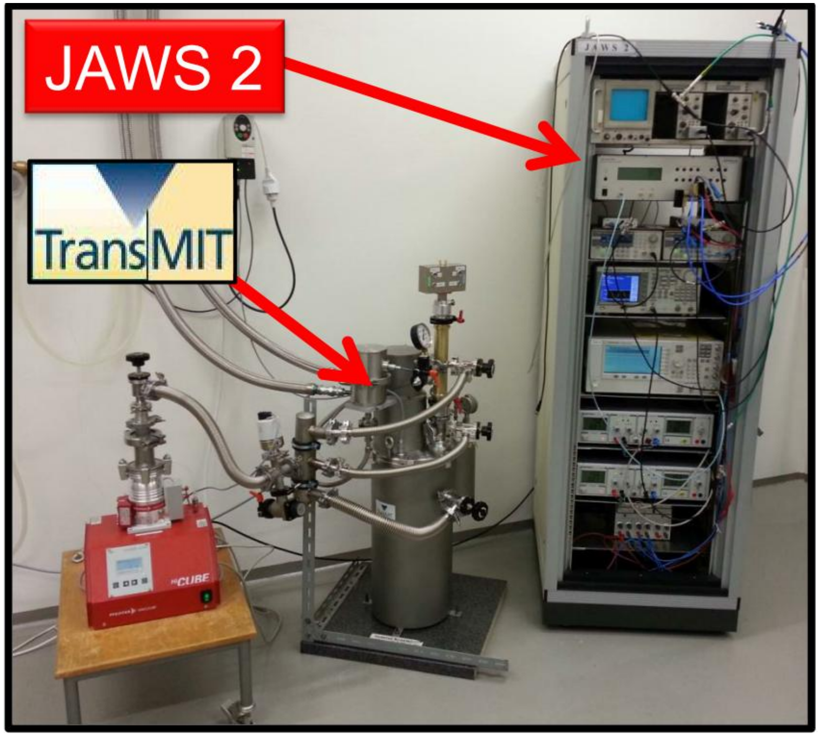
Cryocooler for pulse-driven Josephson arrays



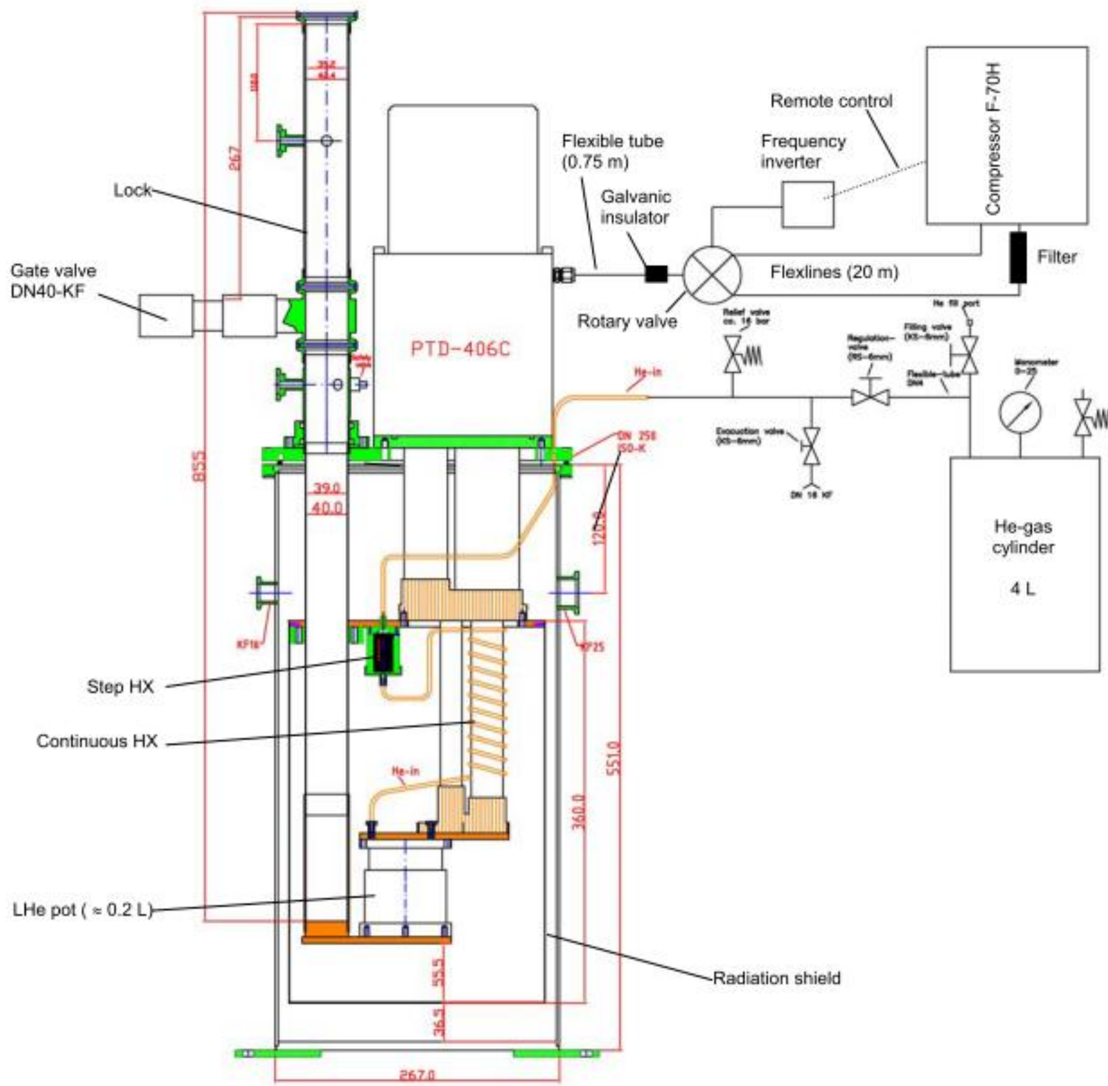


- Low RF power due to pulsed operation
- TransMIT Pulse Tube Cooler ($\Delta T \approx 2$ mK)
- Lowest temperature with cryoprobe ≈ 3K
- Arrays are cooled by He as exchange gas
- simultaneous operation of two arrays on one chip possible
- No LHe necessary!

http://cryo.transmit.de/

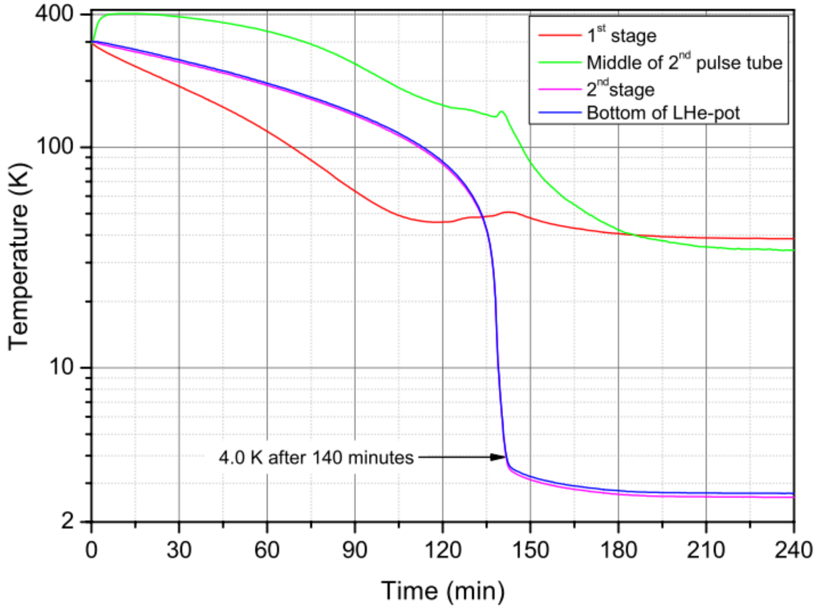


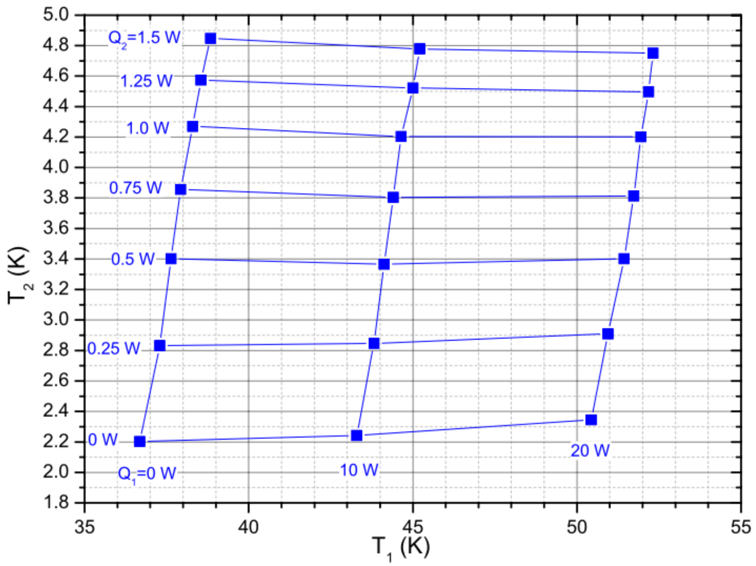
TransMIT Cryocooler



TransMIT Cryocooler

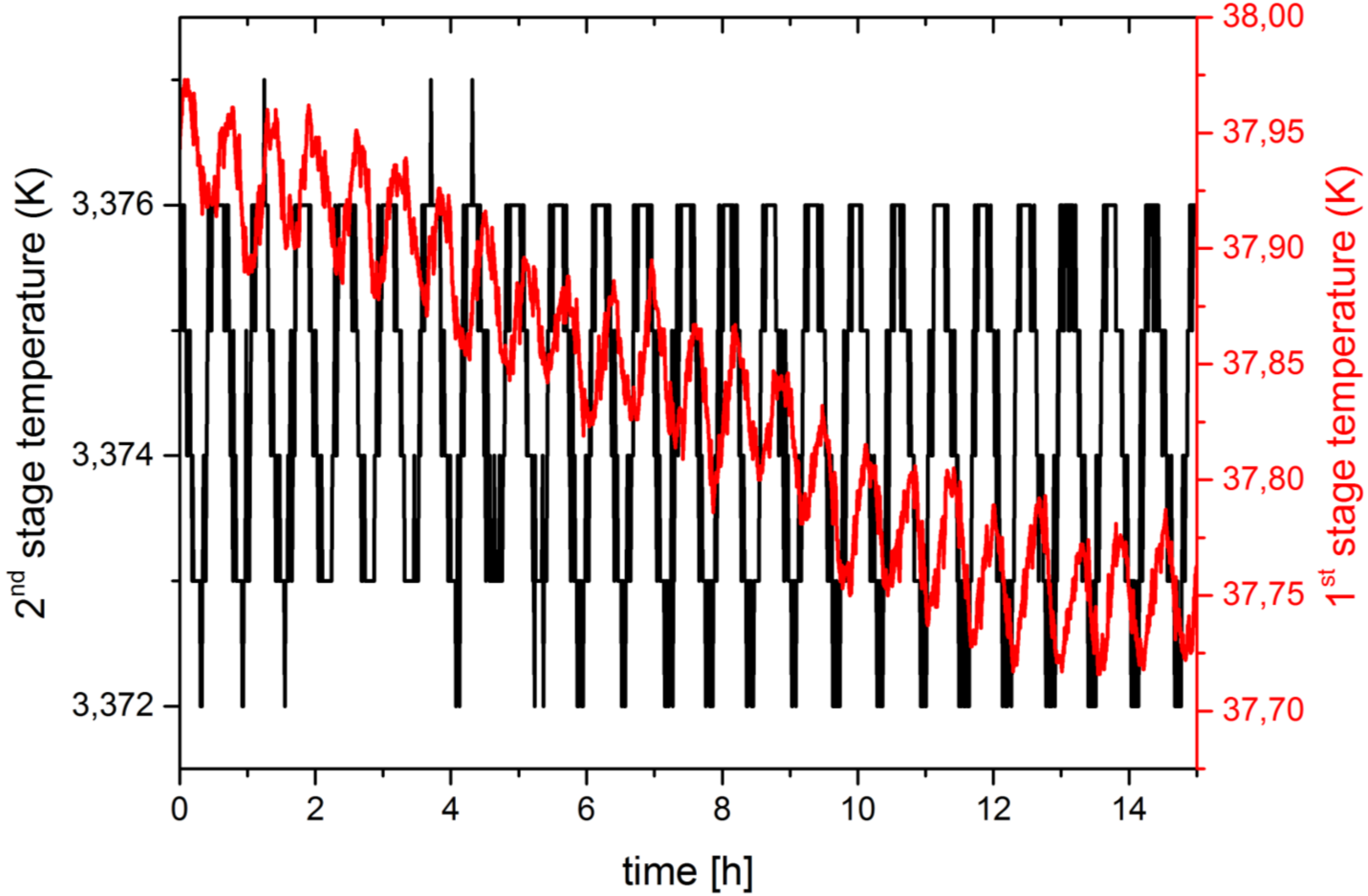
- Cool down time approx. 2.5 h
- 3 h when cryoprobe is already inserted
- Simply switch on when needed





- Cooling power approx. 1 W @ 4.2 K
- About 0.2 W are needed for Top-loading tube and LHe pot
- 0.1 W for cryoprobe

TransMIT Cryocooler



- Temperature oscillation damped to 2 mK by LHe pot (65 ml LHe)
- Best performance below 4 K

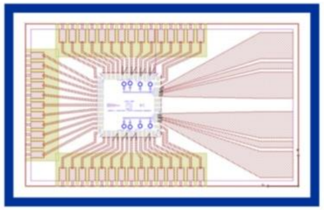
JAWS reminder

Pulse-driven Josephson Arrays

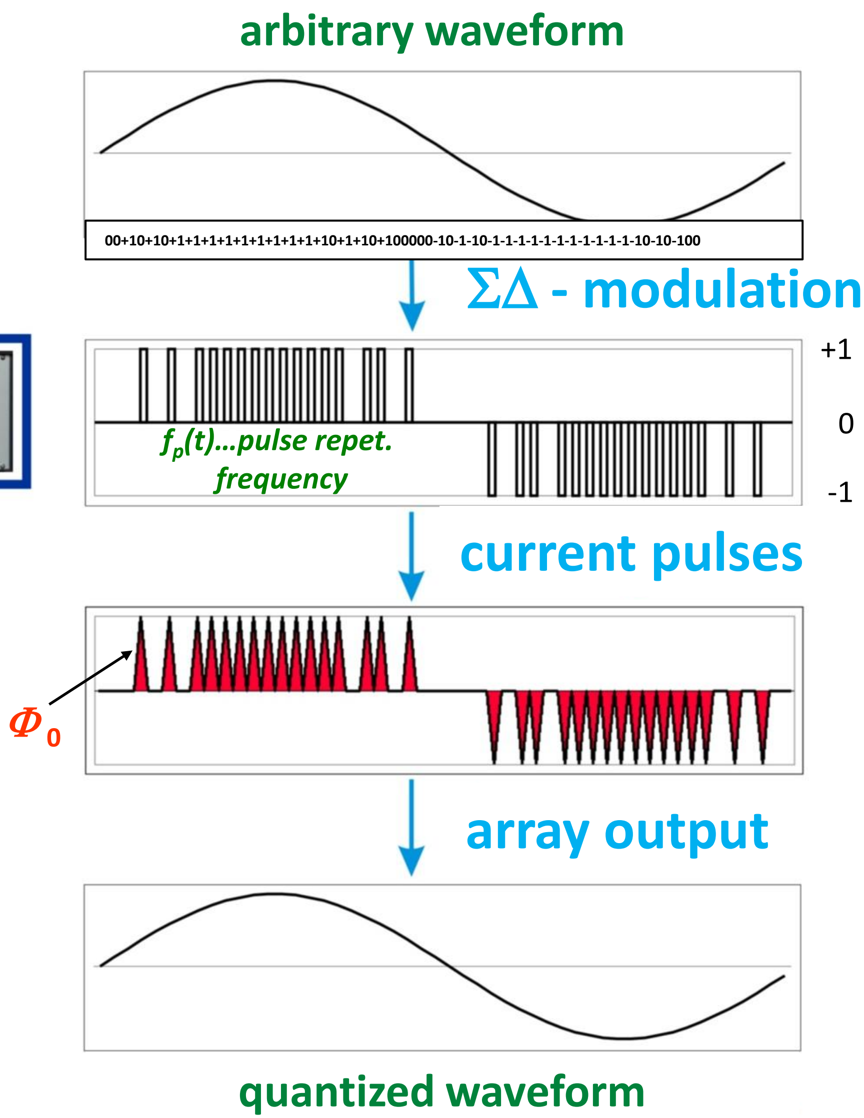
computer

pulse-pattern-generator (PPG)

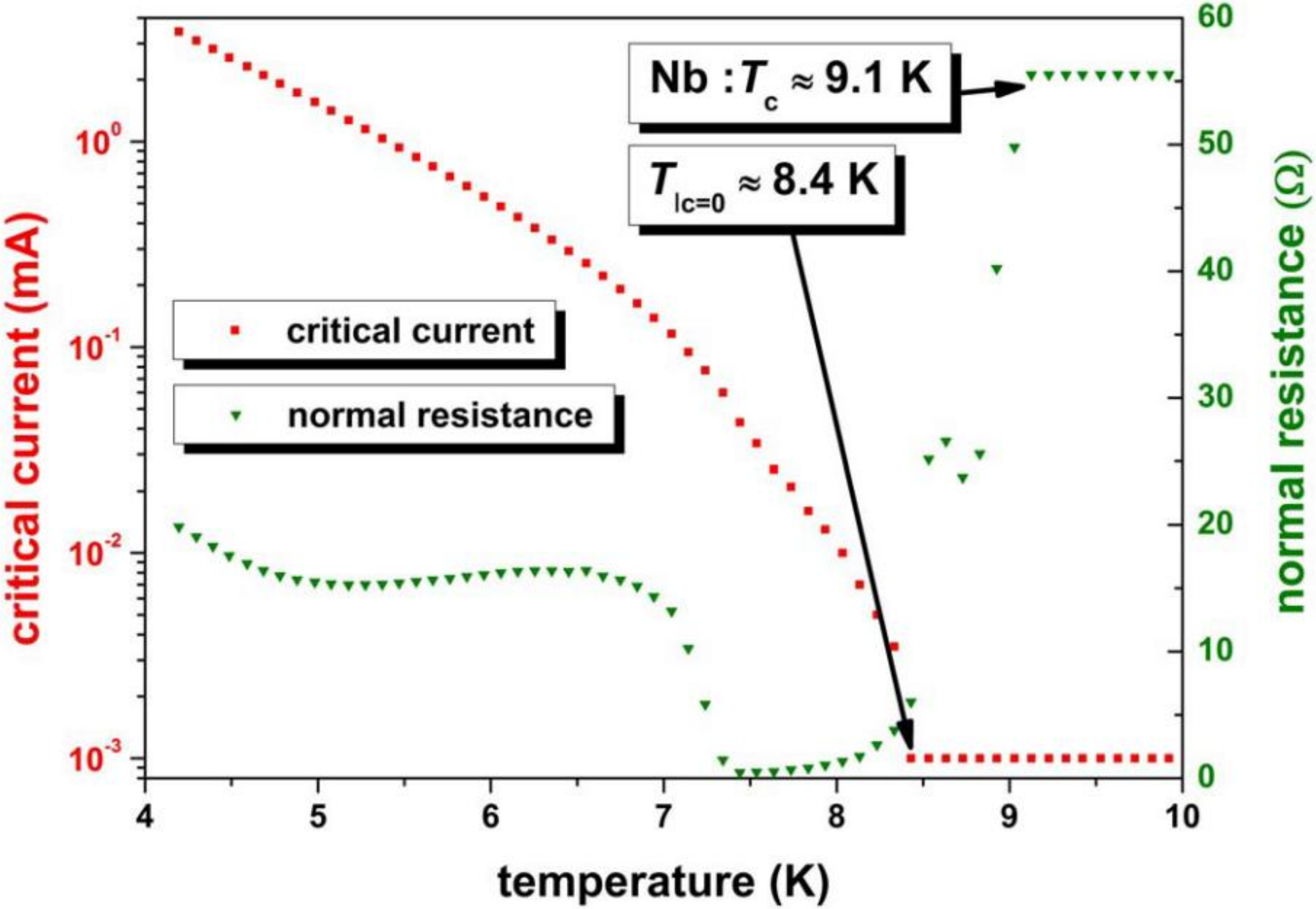
SNS JAWS chip @ LHe : 4.2 K



spectrum analyzer

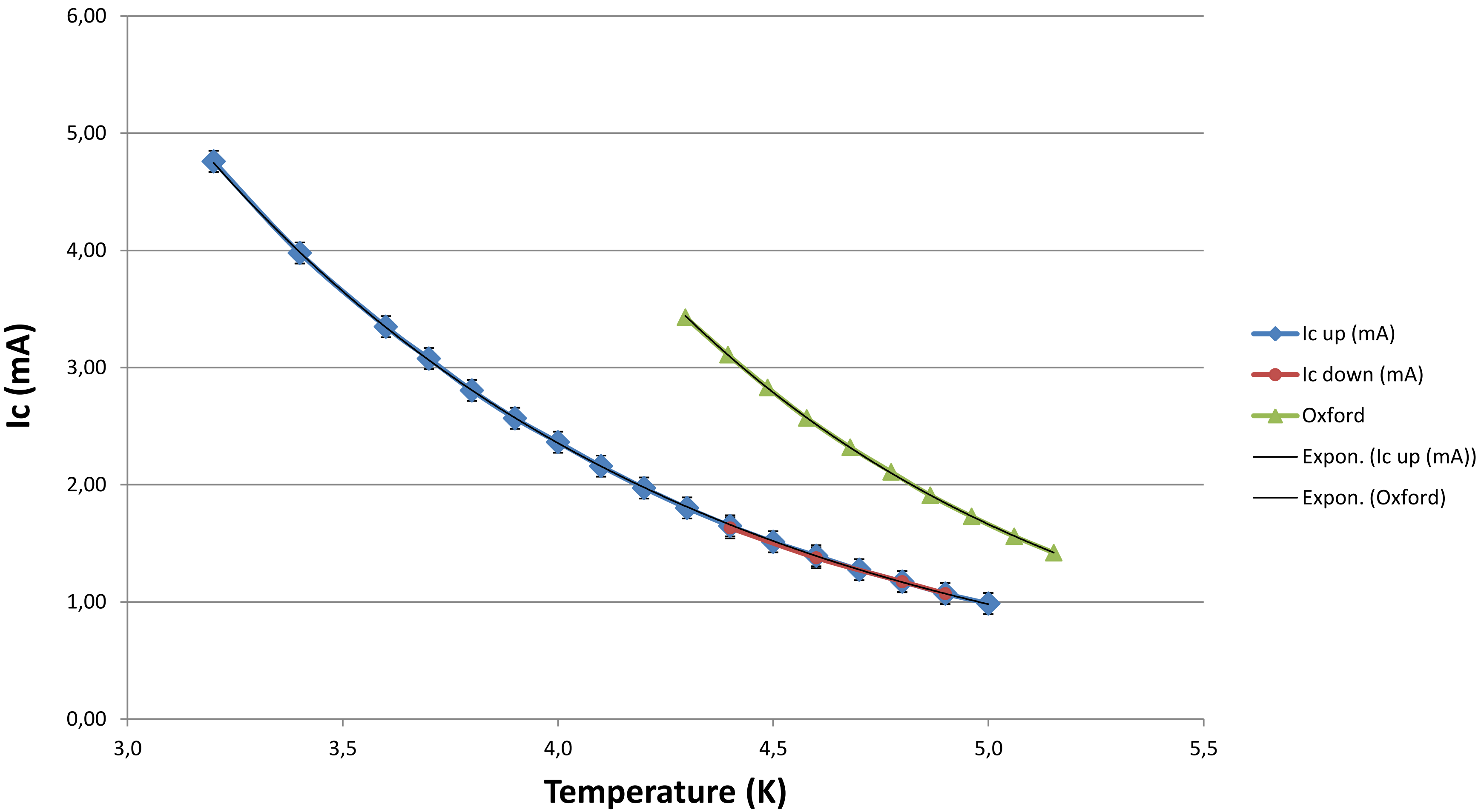


First measurements in cryocooler

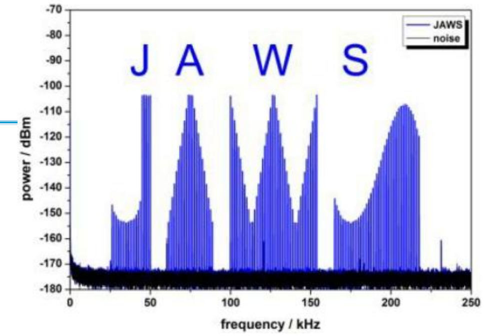


Kieler et al., World Journal of Condensed Matter Physics, 2013, 3, 189-193
http://dx.doi.org/10.4236/wjcmp.2013.34031

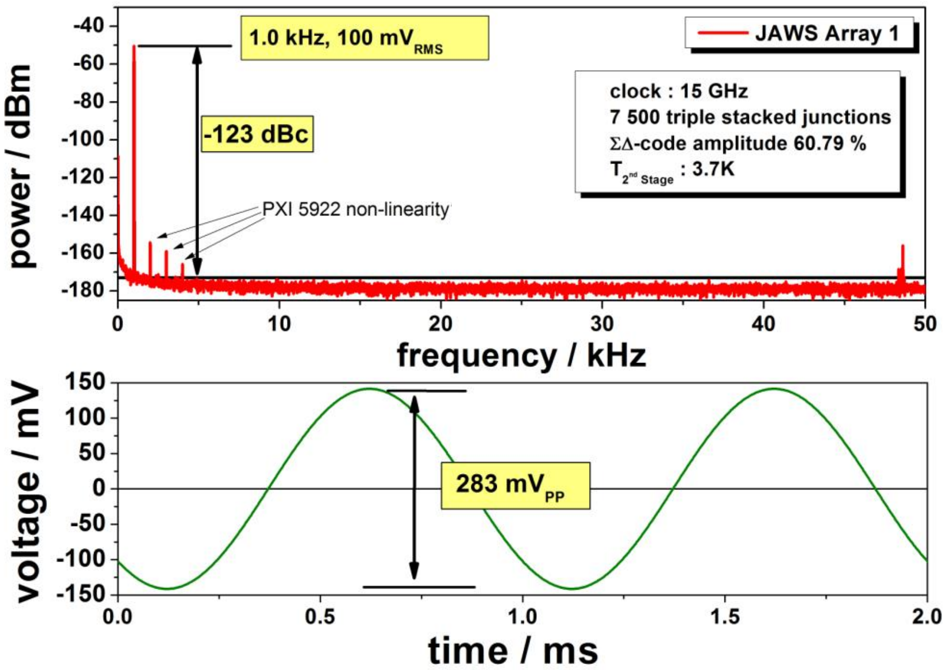
First measurements in cryocooler

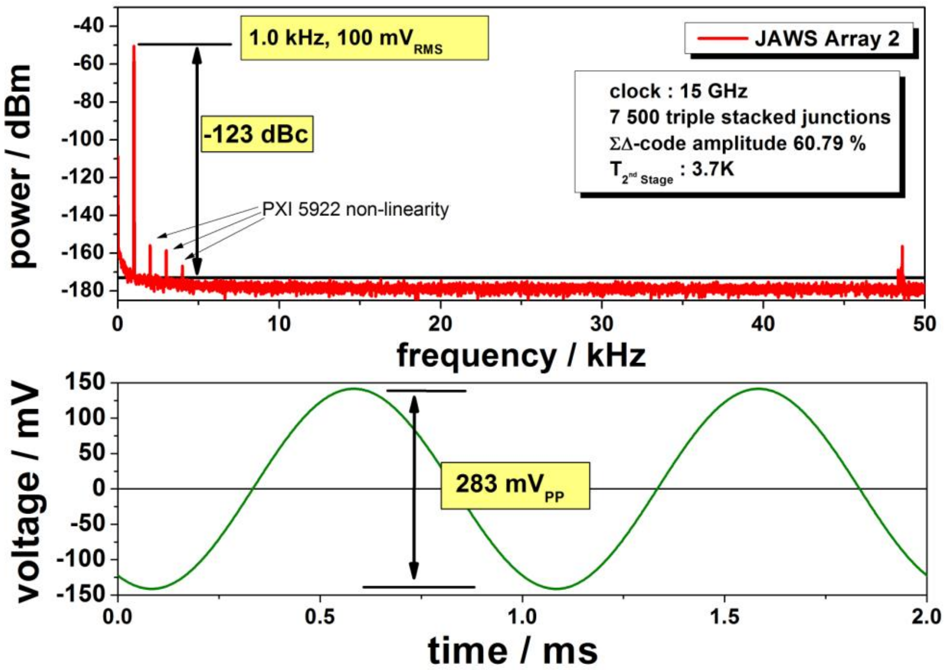


First measurements in cryocooler



- Noise floor comparable to measurements in LHe
- 100 mV_{RMS} with arrays of 6000 junctions is possible
- Up to four arrays with 125 mV_{RMS} should be possible
- Crosstalk between both arrays is in the order of some parts in 10^8
- Two independent voltages are needed for the application in an impedance bridge





Summary

- Cryocoolers to avoid LHe logistic
- Pulse-Tube cooler has the advantage of no moving parts
- Temperature below 4.2 K can easily be reached
- Two methods of mounting (fixed on 2^{nd} stage / mounted on cryoprobe)
- A certain infrastructure is needed to operate such a system
- Top-loading systems make fast change of samples possible
- Limitations due to heat conductance of exchange gas
- Simultaneous operation of two JAWS arrays

Thank you for your attention!

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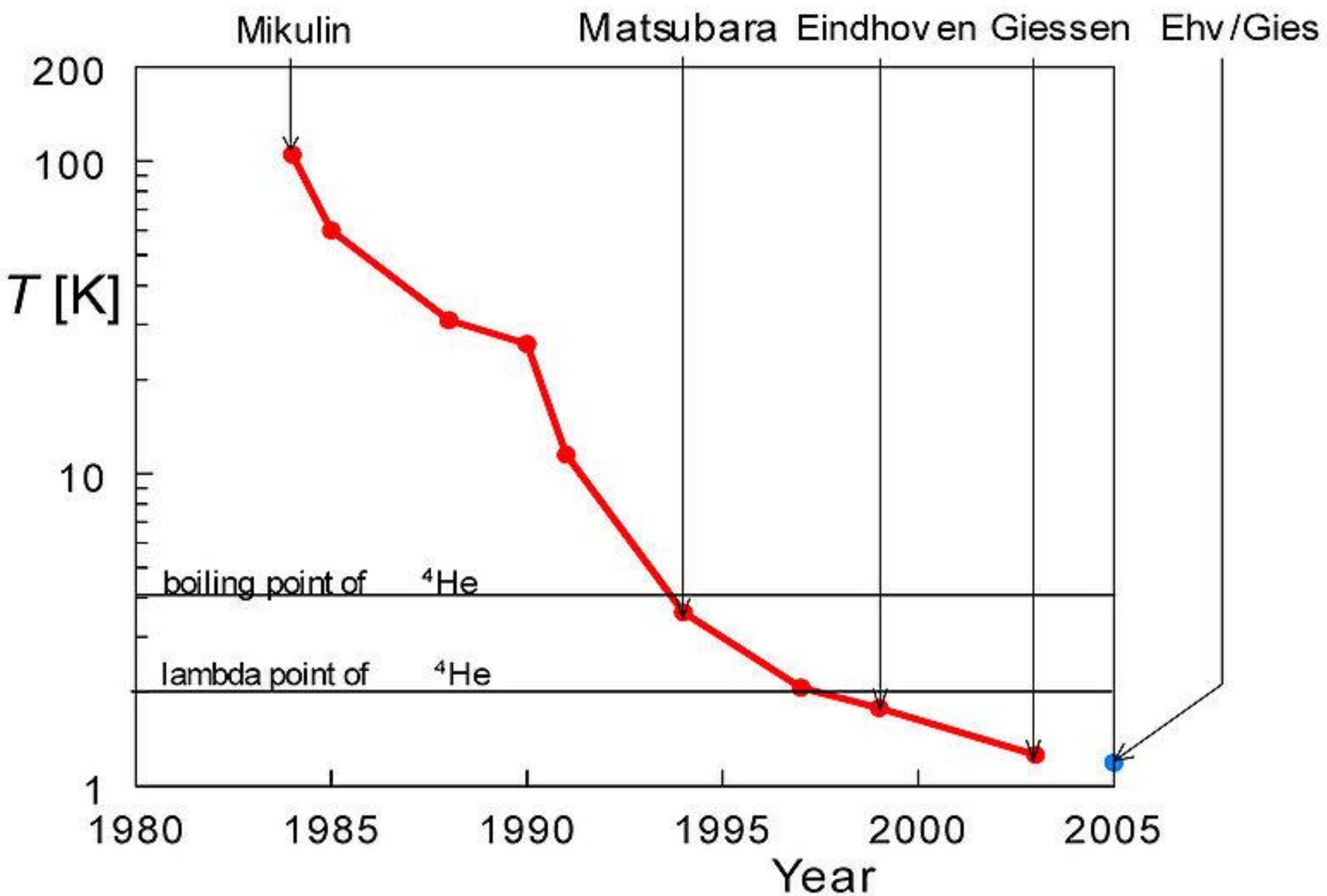
Stand: 06/2015

Pulse-Tube cryocooler



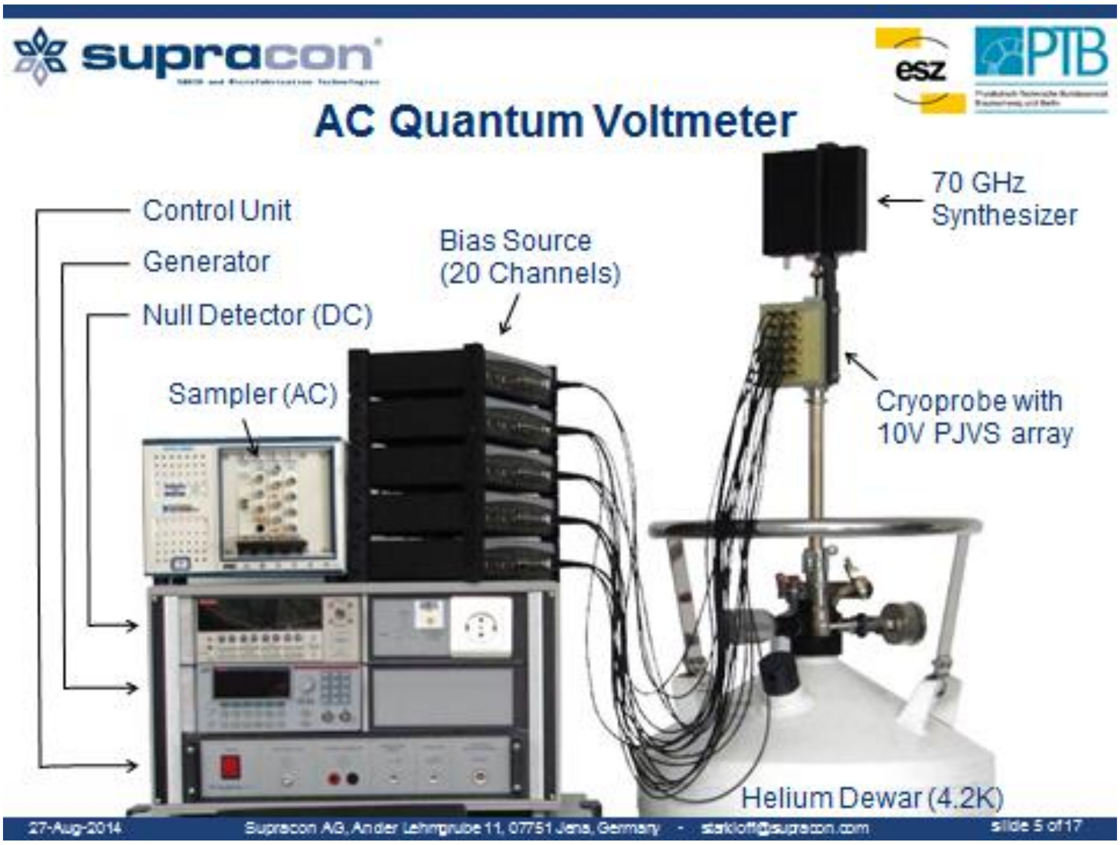
Picture: Mbeljaars (Wikipedia)

2015

Practical Training ACQ-PRO

Table of Contents

1 Parts list of the AC Quantum Voltmeter system

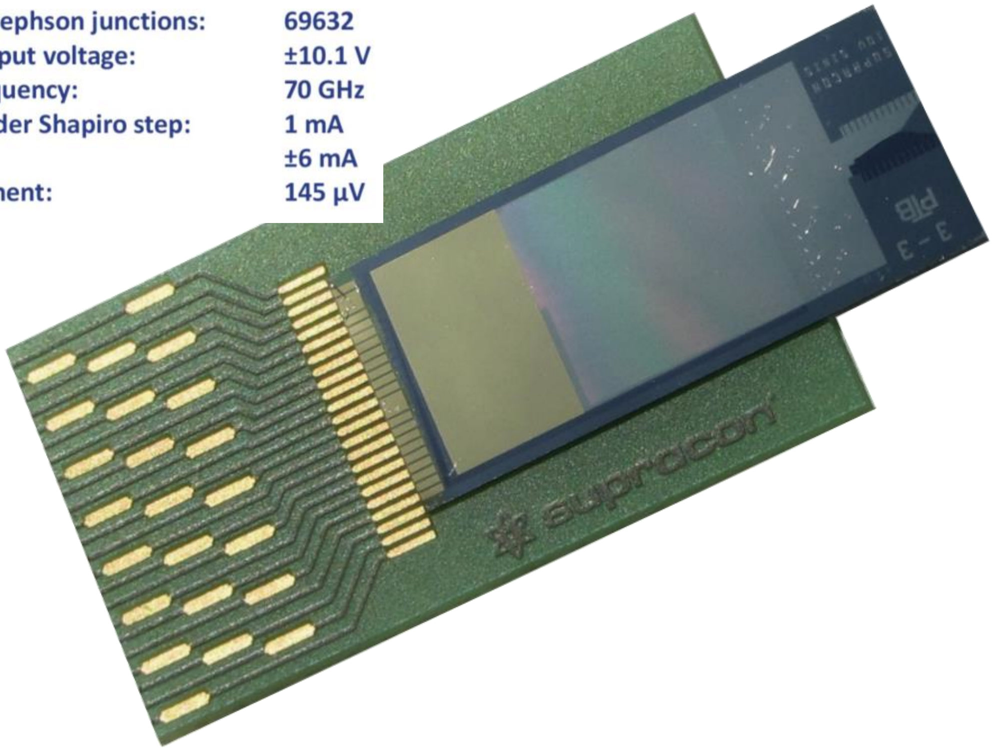


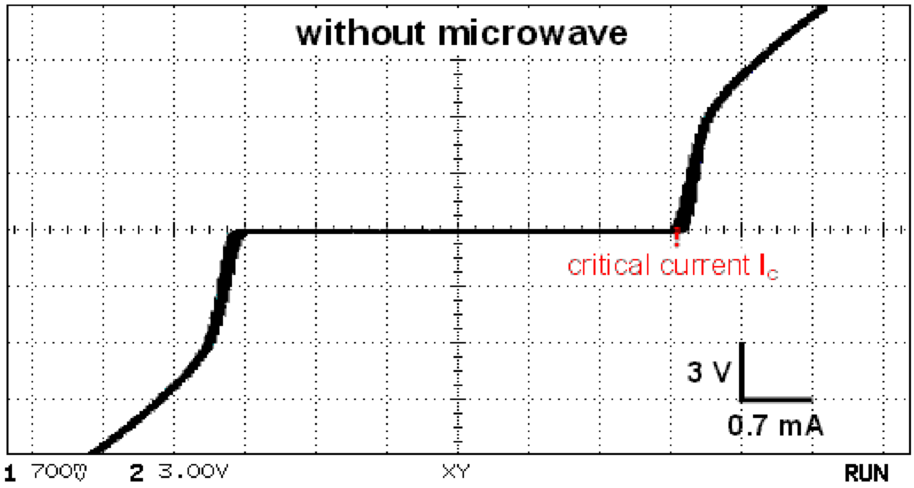
The AC Josephson system consists of the following units:

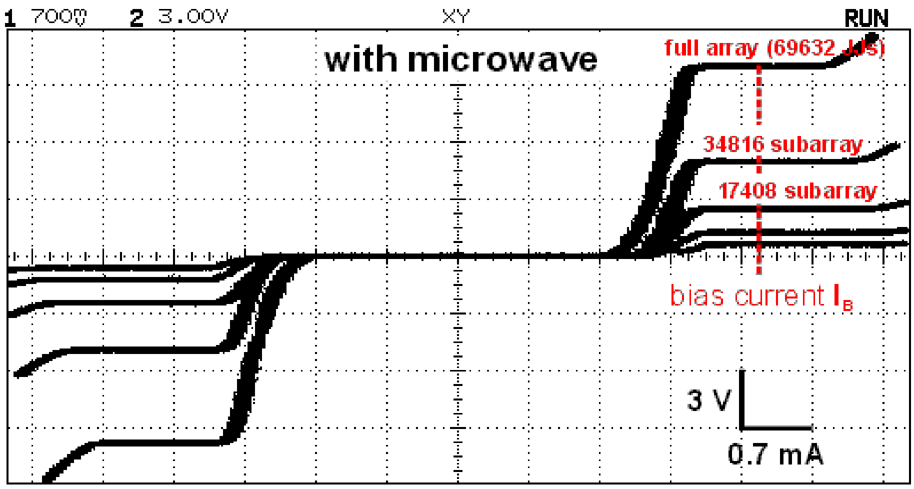
1. **Cryoprobe** with **programmable Josephson junction array chip** (PTB)
2. **70 GHz microwave synthesizer** (Jülicher Squid GmbH)
3. **Bias sources** (5 LeCroy units)
4. **Keithley 2182A** nanovoltmeter
5. **Electronic box**
6. **Waveform generator** Keithley 3390
7. **Synchronisation units**
   a. Optical Trigger IN/OUT units with fibre connection
   b. Optical Clock IN/OUT units with fibre connection
8. **PXI 1036,** 6-slot Chassis with
   a. PXI 8336 (optical communication to computer)
   b. **PXI 5922** (digitizer, sampler respectively)
   c. Optical fibre cable
9. **Multiplexer** with polarity switch
10. **Computer**
    a. PCI8336 card (for communication to PXI 1036)
    b. LabView installed
    c. Two free USB ports
11. **USB hub** units
    a. Optical isolated USB-hub (two units) with twisted multimode fibre connection
    b. Grounded USB hub 7-port (for control box, synthesizer and USB-IEEE converter)
12. **Power supply**
    a. Isolation transformer 12V & 5V power supply (PTB)
    b. Battery 12 V power supply with charger (Supracon)

2 Basics of the 10V PJVS array

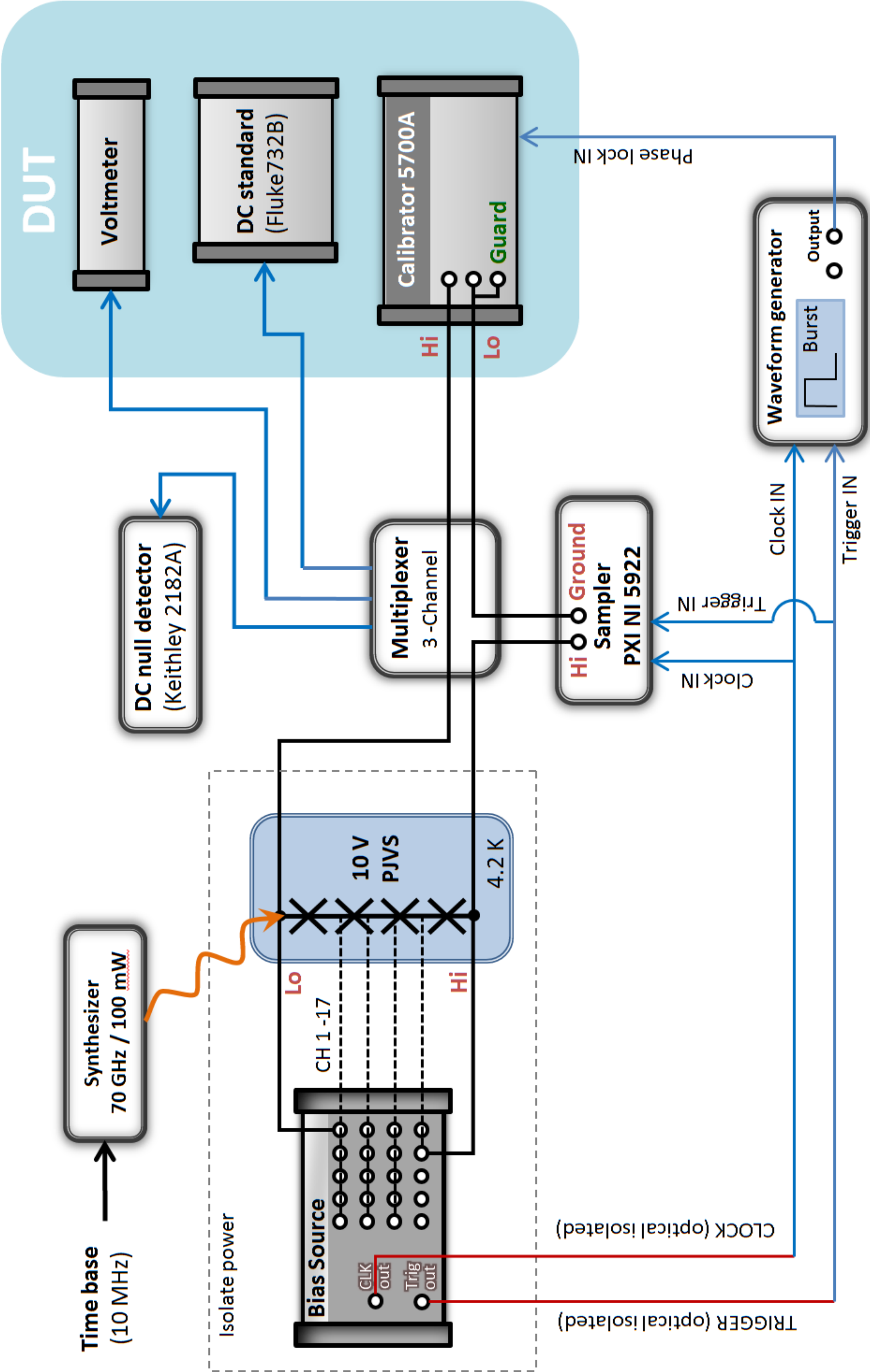
- **Number of Josephson junctions:** 69632
- **Maximum output voltage:** ±10.1 V
- **Operating frequency:** 70 GHz
- **Zero & first order Shapiro step:** 1 mA
- **Bias current:** ±6 mA
- **Voltage increment:** 145 µV





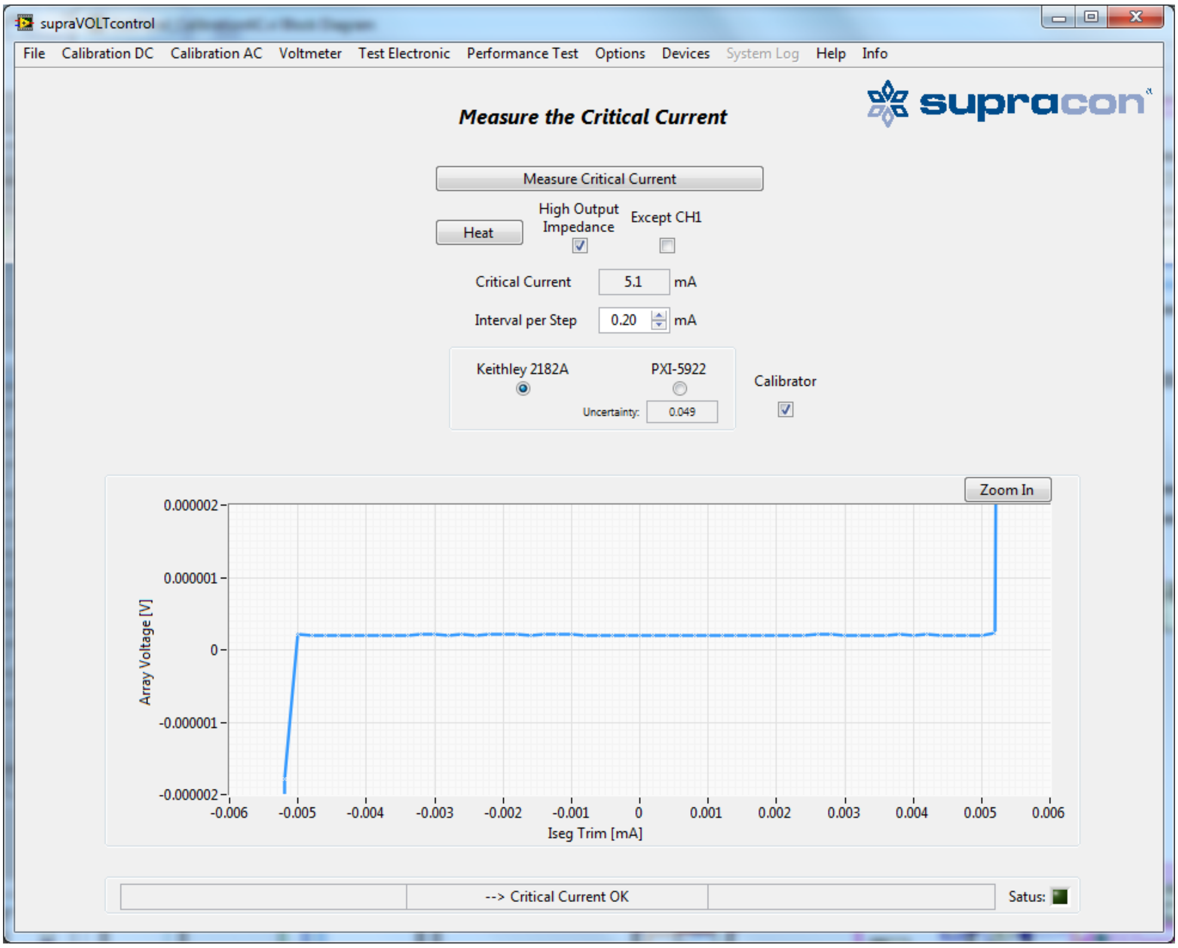


3 Setup of the AC Quantum Voltmeter



4 Performance tests

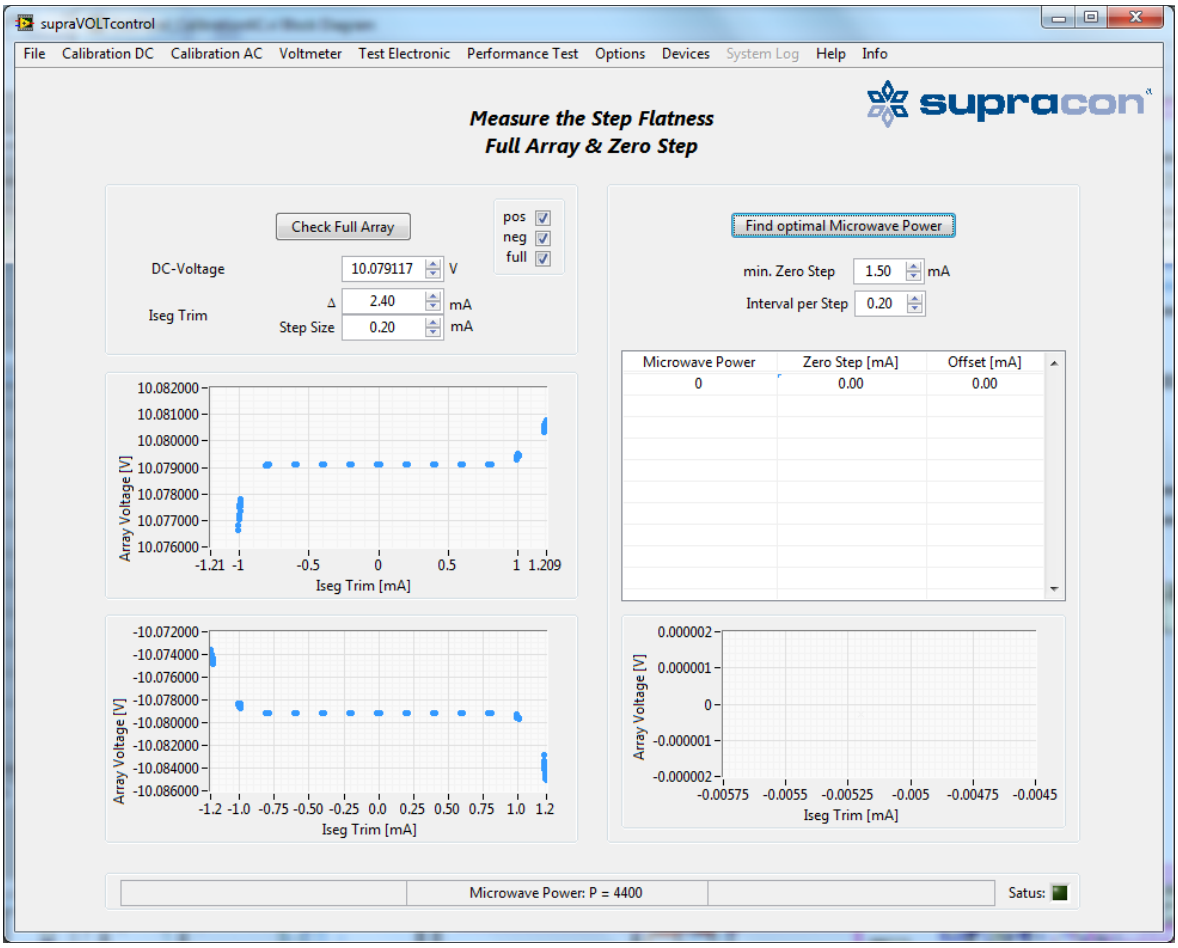
4.1 Critical current of the JVS array



The most important parameter of the JVS array is the critical current. Its value is saved in the binary.ini file. In some cases, for example switching events, or parasitic noise, or disturbances due to ground loops, or cross talk from trigger/ clock signals etc. the critical current can be suppressed and the operating margins decrease. Therefore it is recommended to check the critical current from time to time.

In the case the critical current is supressed magnetic flux is trapped in the Josephson junctions. The trapped magnetic flux can be removed by heating the JVS array above its critical temperature, typically about T=10K for the used niobium superconductor. Therefore a heater is integrated near the chip and addressable by the software. When the magnetic flux is removed the critical current should be reach its nominal value.

4.2 Width of the Josephson voltage step



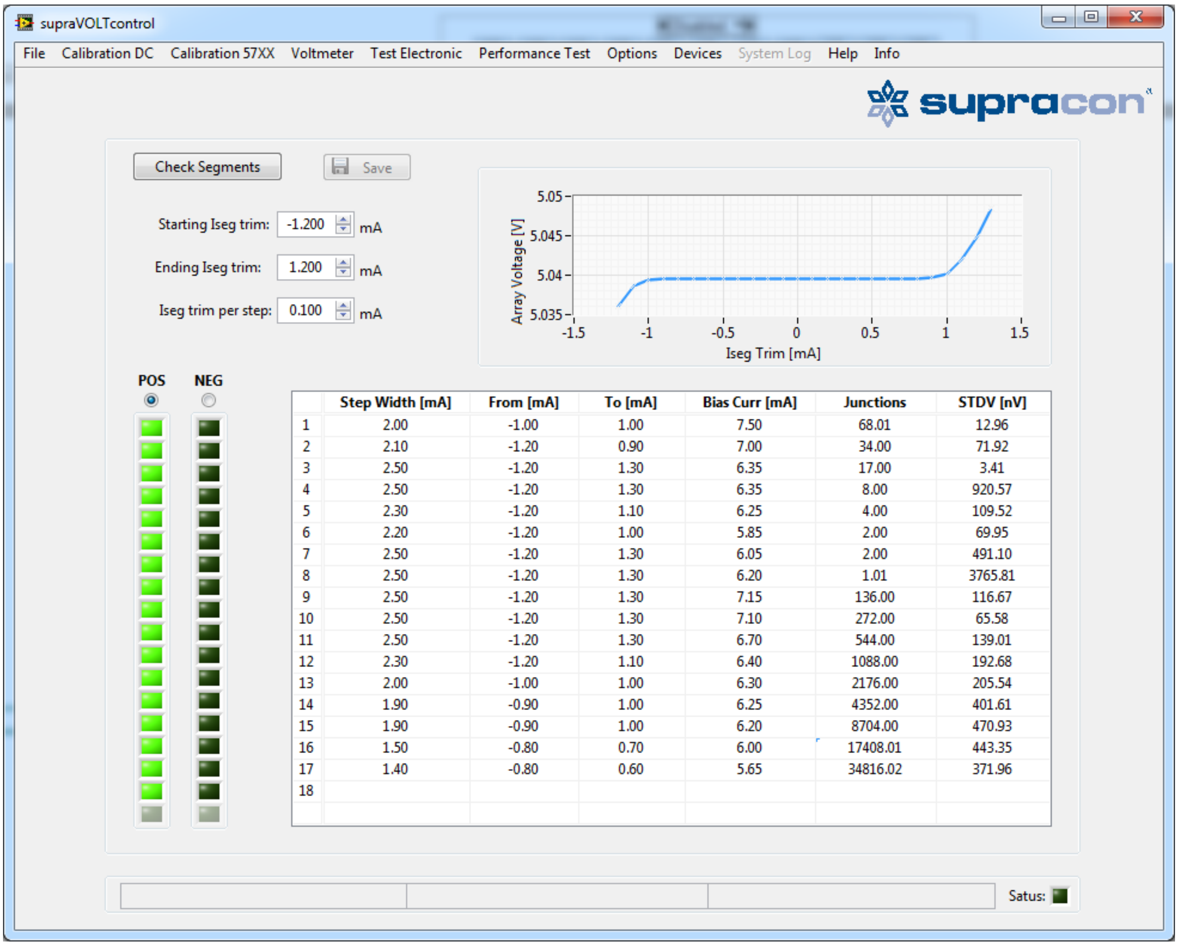
Another important parameter of the Josephson junction array is the current width of the constant voltage step under microwave irradiation. These voltage steps also called Shapiro steps determine the performance of the JJA and with it of the complete system. Larger steps increase the operating margins as the bias current can vary over a wider range and improve noise immunity.

The step width is measurable by applying an additional trim current to all segments of the JVS array. During this trim current sweep the voltage is measured and the step width is given by the part of a flat region where the voltage is constant.

4.3 Microwave power

The microwave power can be tuned for optimisation the zero current step. By running this test, the microwave power is increased stepwise and the corresponding zero current step is measured and displayed. The minimal zero step width should be 1.5 mA, this is the default value.

4.4 Bias current I_B



Each Josephson segment must be driven with the correct bias current I_B, to be on a Josephson step. The individual bias currents of each segment are stored in the binary.ini file. For an optimal performance with best operating margins it is recommend optimizing the bias current to the centre of the Shapiro steps.

```
[BinArray_ PTB8-8]
no_of_segments = 17
segments(lo-->hi) = "68, 34, 17, 8, 4, 2, 2, 1, 136, 272, 544, 1088, 2176, 4352, 8704, 17408, 34816"
code_strategy = "binary"
bias_data_segment_0 = "I_minus=-3.85 mA, w_minus=1.7 mA, I_zero=0 mA, w_zero=1 mA,I_plus=4.5 mA, w_plus=1.6 mA"
bias_data_segment_1 = "I_minus=-3.55 mA, w_minus=1.7 mA, I_zero=0 mA, w_zero=1 mA,I_plus=4.2 mA, w_plus=1.6 mA"
bias_data_segment_2 = "I_minus=-3.25 mA, w_minus=1.5 mA, I_zero=0 mA, w_zero=1 mA,I_plus=4 mA, w_plus=1.6 mA"
bias_data_segment_3 = "I_minus=-3.15 mA, w_minus=1.7 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.25 mA, w_plus=1.7 mA"
bias_data_segment_4 = "I_minus=-3.15 mA, w_minus=1.7 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.25 mA, w_plus=1.7 mA"
bias_data_segment_5 = "I_minus=-3.15 mA, w_minus=1.7 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.25 mA, w_plus=1.7 mA"
bias_data_segment_6 = "I_minus=-3.05 mA, w_minus=1.5 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.5 mA, w_plus=1.6 mA"
bias_data_segment_7 = "I_minus=-3.05 mA, w_minus=1.5 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.3 mA, w_plus=1.4 mA"
bias_data_segment_8 = "I_minus=-3.25 mA, w_minus=1.5 mA, I_zero=0 mA, w_zero=1 mA,I_plus=4.2 mA, w_plus=1.2 mA"
bias_data_segment_9 = "I_minus=-3.25 mA, w_minus=1.3 mA, I_zero=0 mA, w_zero=1 mA,I_plus=4.15 mA, w_plus=1.1 mA"
bias_data_segment_10 = "I_minus=-3.15 mA, w_minus=1.1 mA, I_zero=0 mA, w_zero=1 mA,I_plus=4 mA, w_plus=1.2 mA"
bias_data_segment_11 = "I_minus=-3 mA, w_minus=1 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.95 mA, w_plus=1.1 mA"
bias_data_segment_12 = "I_minus=-3 mA, w_minus=1 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.85 mA, w_plus=1.1 mA"
bias_data_segment_13 = "I_minus=-2.95 mA, w_minus=1.1 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.7 mA, w_plus=1.2 mA"
bias_data_segment_14 = "I_minus=-2.95 mA, w_minus=1.1 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.6 mA, w_plus=1.2 mA"
bias_data_segment_15 = "I_minus=-3 mA, w_minus=0.8 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3.4 mA, w_plus=1 mA"
bias_data_segment_16 = "I_minus=-2.85 mA, w_minus=0.7 mA, I_zero=0 mA, w_zero=1 mA,I_plus=3 mA, w_plus=0.8 mA"
```

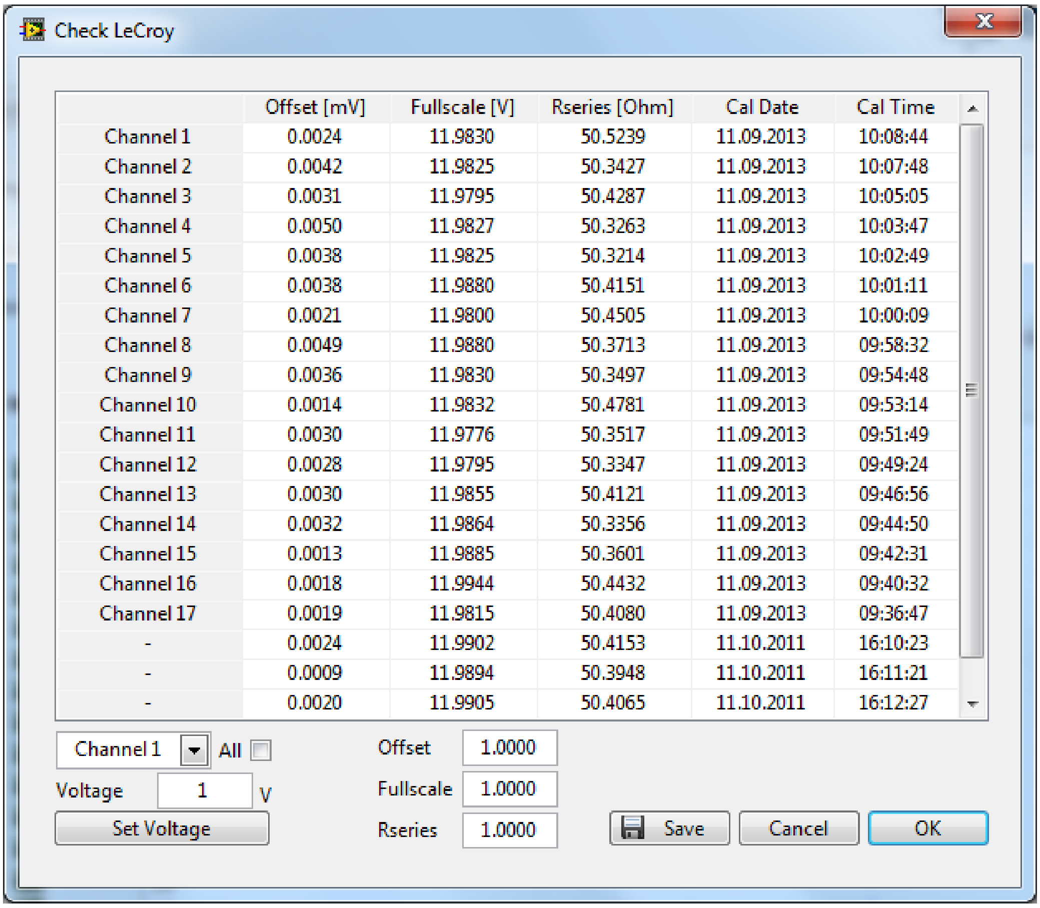
4.5 Microwave frequency

This performance test is under construction ….

The microwave frequency can be tuned by the synthesizer in the range from 69 GHz till 71 GHz. As the Shapiro step performance of the JJA depends on the driving frequency it can be useful to tune the frequency to its optimal value. This can be done by using the software tool "…".

4.6 Calibration bias sources

The bias sources are used to drive the JVS array segments. From time to time it is recommended calibrating their output voltage in terms of offset, gain and internal resistance. Please follow the instructions below.

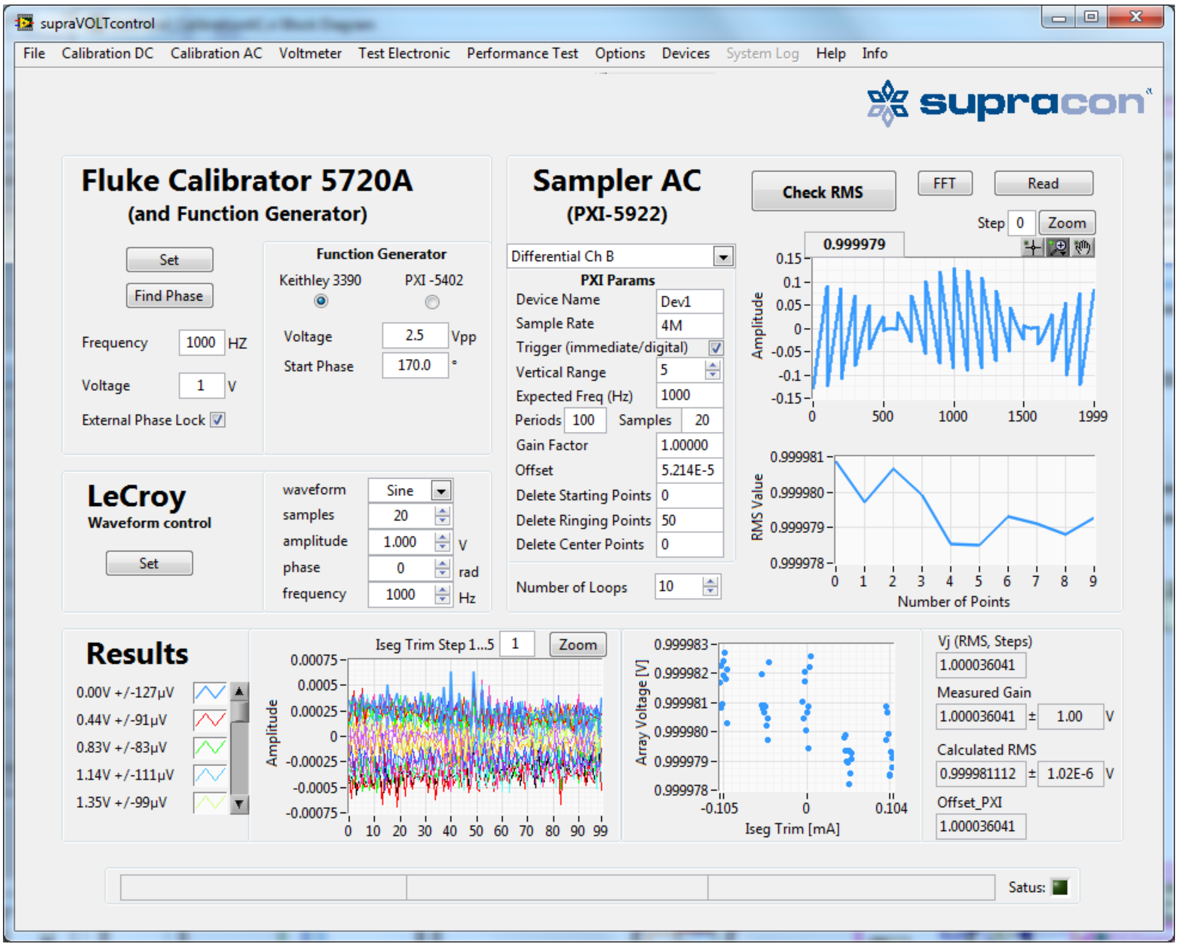


	Offset [mV]	Fullscale [V]	Rseries [Ohm]	Cal Date	Cal Time
Channel 1	0.0024	11.9830	50.5239	11.09.2013	10:08:44
Channel 2	0.0042	11.9825	50.3427	11.09.2013	10:07:48
Channel 3	0.0031	11.9795	50.4287	11.09.2013	10:05:05
Channel 4	0.0050	11.9827	50.3263	11.09.2013	10:03:47
Channel 5	0.0038	11.9825	50.3214	11.09.2013	10:02:49
Channel 6	0.0038	11.9880	50.4151	11.09.2013	10:01:11
Channel 7	0.0021	11.9800	50.4505	11.09.2013	10:00:09
Channel 8	0.0049	11.9880	50.3713	11.09.2013	09:58:32
Channel 9	0.0036	11.9830	50.3497	11.09.2013	09:54:48
Channel 10	0.0014	11.9832	50.4781	11.09.2013	09:53:14
Channel 11	0.0030	11.9776	50.3517	11.09.2013	09:51:49
Channel 12	0.0028	11.9795	50.3347	11.09.2013	09:49:24
Channel 13	0.0030	11.9855	50.4121	11.09.2013	09:46:56
Channel 14	0.0032	11.9864	50.3356	11.09.2013	09:44:50
Channel 15	0.0013	11.9885	50.3601	11.09.2013	09:42:31
Channel 16	0.0018	11.9944	50.4432	11.09.2013	09:40:32
Channel 17	0.0019	11.9815	50.4080	11.09.2013	09:36:47
-	0.0024	11.9902	50.4153	11.10.2011	16:10:23
-	0.0009	11.9894	50.3948	11.10.2011	16:11:21
-	0.0020	11.9905	50.4065	11.10.2011	16:12:27

1) Let warm up the Lecroy bias source as well as the Keithley nanovoltmeter for more than 3 hours.
2) Make a copy of the binary.ini file
3) Select the user interface <*Performance Test*> → <*Check LeCroy*> and choose the LeCroy channel no. which should be calibrated.
4) Connect the BNC output of that LeCroy channel no. to the input of the Keithley 2182A nanovoltmeter by using a matched cable.
5) Type a <Voltage> of 10 V and start measurement with <Set Voltage>. The offset and gain are measured and if finished the results are displayed in the table
6) Continue with next LeCroy channel.
7) When all channels are measured, store the data to the binary.ini file with the <Save> button

4.7 Set AC devices

For investigation AC voltage measurements in dependence of various parameters, for example sampling rate, Josephson sampling frequency, or an arbitrary frequency selection etc. the performance test <*Set AC devices*> is useful.



The desired <Frequency> and <Voltage> are set in the **Fluke Calibrator 5720A** field, and the most interesting parameters are <Sample rate>, <Deleting Starting Points>, Deleted Ringing Points>, <Deleted Center Points>, <Periods> in the <**Sampler AC**> field. The sampling method can be chosen with the pop up menu directly below (PXI-5922), in the figure <Differential Ch B> is shown as example.

With button <Check RMS> the measurement is started.

The spectrum of the measurement data can be done with <FFT>.

In the diagram <Zoom> all samples of the Josephson steps are displayed and all steps should be flat, otherwise the number of deleted point is incorrect or the bias current settings of the JVS are out of step or there can be a parasitic crosstalk from the trigger (20*f).

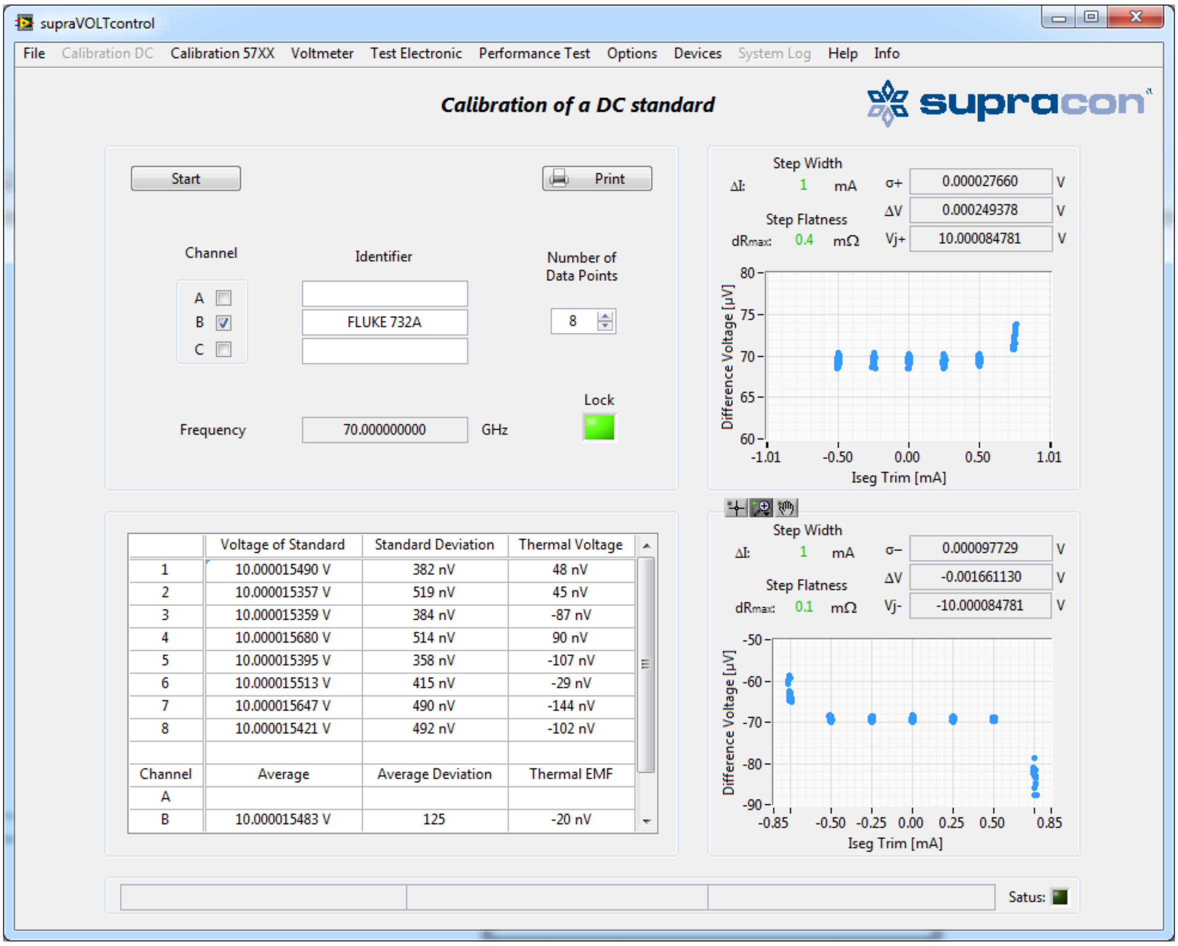
The value of <Periods> should be equal or smaller than the chosen <Frequency>. One measurement value is calculated by the mean of <Periods>, and to get an uncertainty this procedure is repeated by the <Number of Loops>. The Time for one measurement value is given by 1/<Frequency> * <Periods> and should be a multiple of 0.02 s (50 Hz). Typically the measurement time is 0.2s or 1 second.

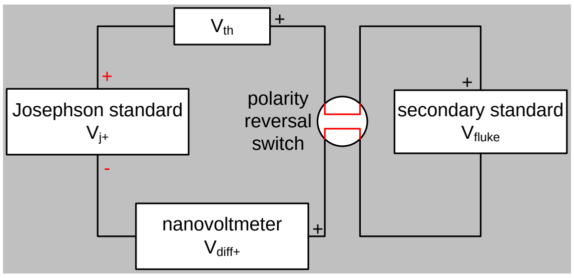
5 DC voltage calibrations

5.1 Calibration of secondary voltage standards

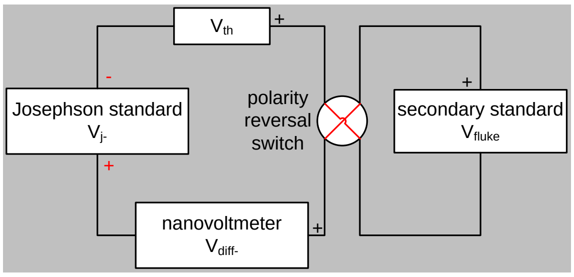
The system is able to calibrate DC voltage standards as well as DC voltmeters.

In the case of DC voltage standard calibrations the Josephson voltage is adjusted to about the voltage of the DUT to measure the difference voltage close to zero, and the nanovoltmeter can be used as null detector. With this method, the noise level of the nanovoltmeter is drastically decreased, and the uncertainty level is improved.





Measurement of the difference voltage V_{diff+} for a positive Josephson voltage V_{j+} setting.



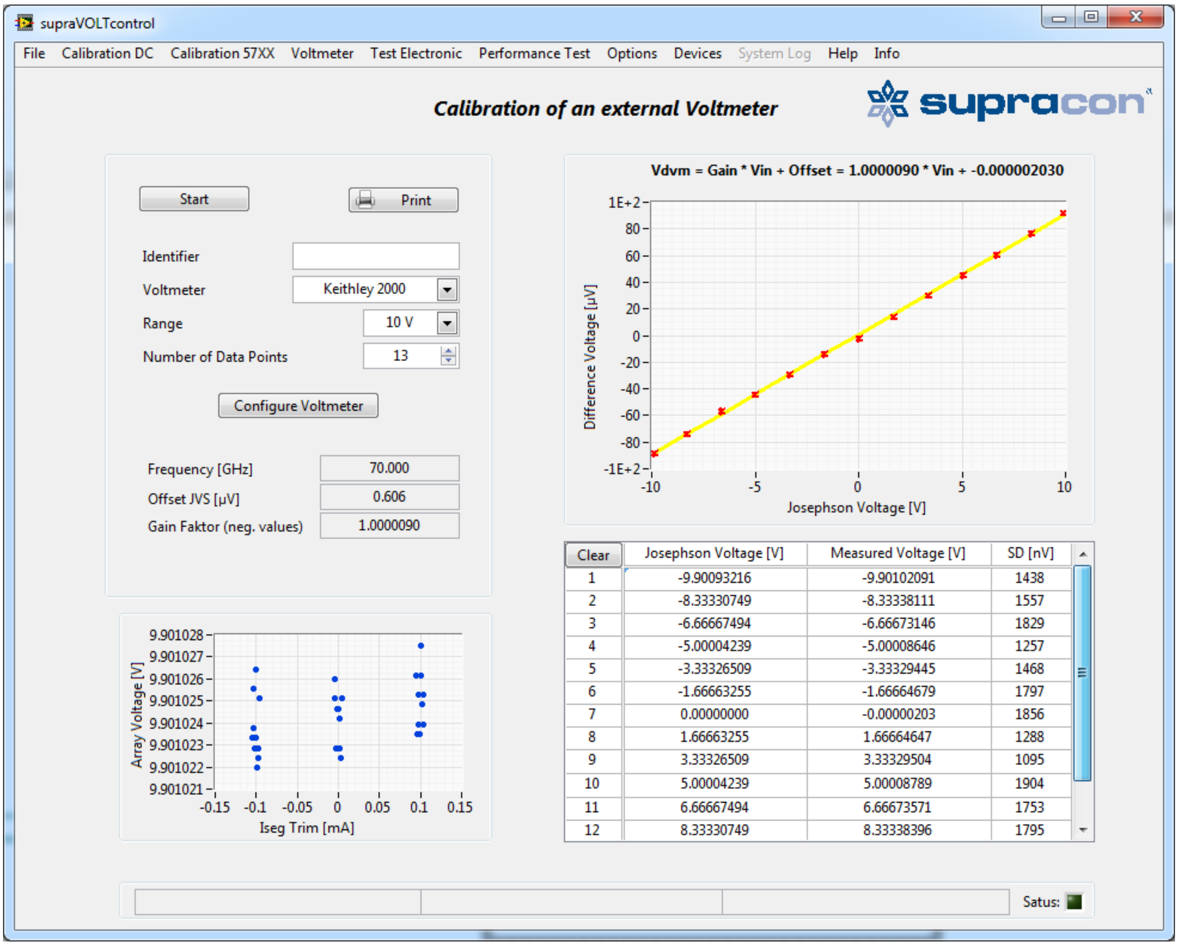
Measurement of the difference voltage V_{diff-} for a negative Josephson voltage V_{j-} setting.

5.2 Calibration of external DC voltmeters

➔ Gain factor and linearity of external voltmeters

$$V_{dvm} = m\ V_{in} + b$$

V_{dvm}	:	measured and displayed voltage of the DVM,
m	:	gain,
V_{in}	:	input voltage of the DVM,
b	:	offset voltage.

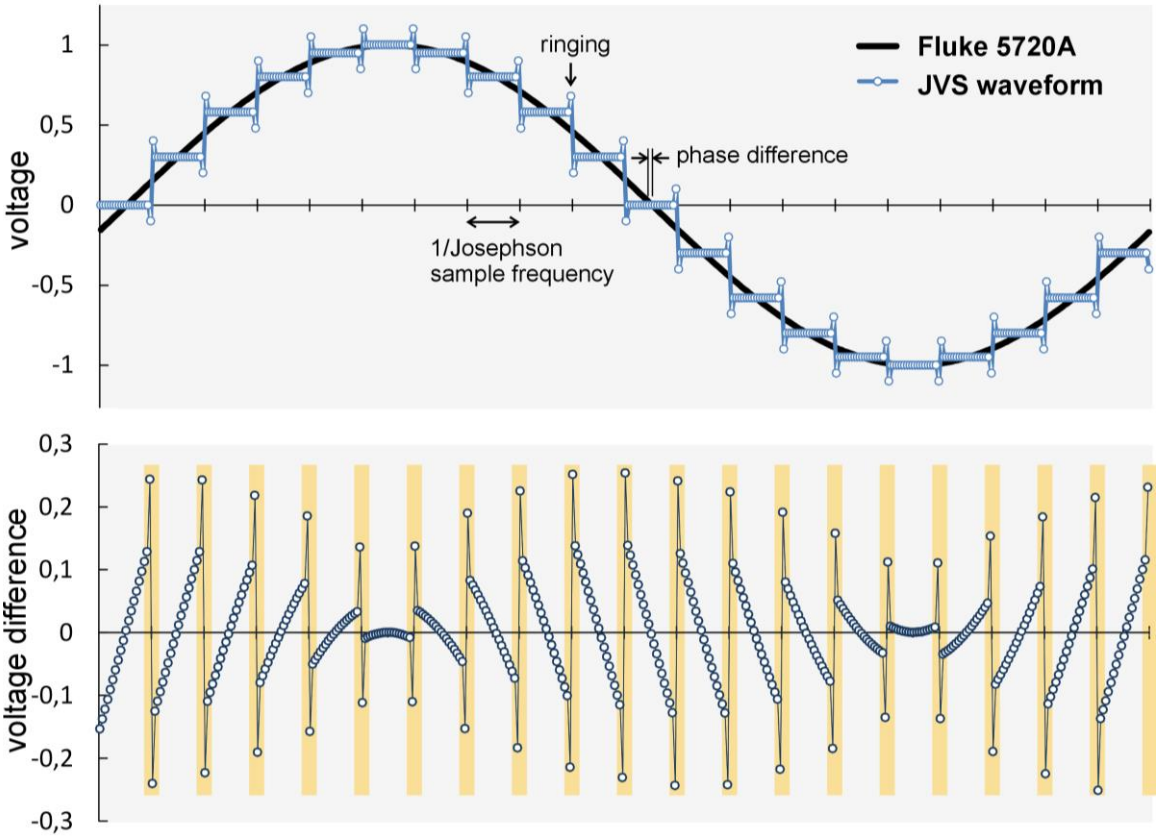


For the following voltmeters the gain *m* can be measured automatically:

- → **Keithley 2182A**
- → **Keithley 2001**
- → **Keithley 2000**
- → **Keithley 182**
- → **Agilent / HP 3457A**
- → **Agilent / HP 3458A**
- → **Agilent / HP 34401A**
- → **Agilent / HP 34420A**
- → **Fluke 8508A**
- → **Datron 1281**

6 AC voltage calibrations

6.1 Sampling technique



One period of the signals from JVS waveform and Fluke calibrator. Upper graph directly sampled and their difference in the lower graph. The JVS array voltage is illustrate with ringing at the point of switching between Josephson steps.

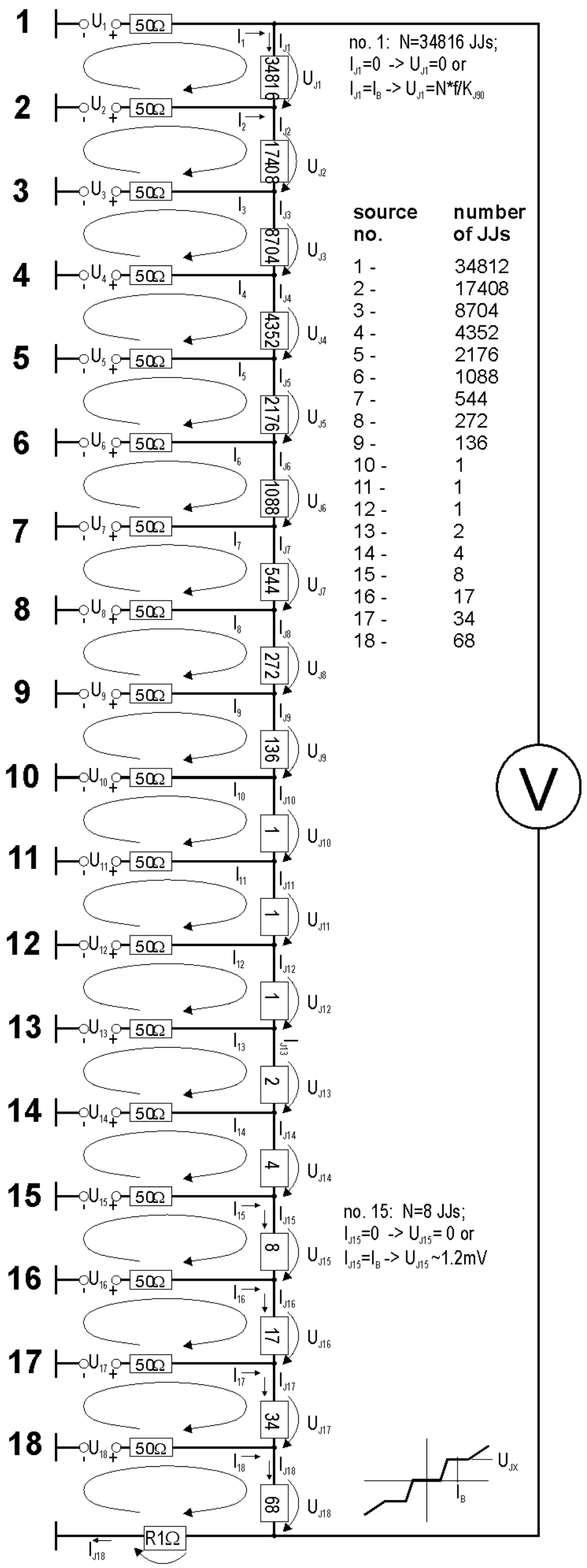
The core of the AC Quantum Voltmeter is a stepped Josephson voltage, called Josephson waveform, with typically 20 steps per period. A comparison of this exact calculable Josephson waveform with an unknown AC voltage enables an accurate determination of the AC voltage. The AC voltage measurement based on a sampling technique, to eliminate parasitic transients which occur during switching between the Josephson voltage steps. These transients are also correlated with ringing at the switching instant. The ringing are due to two effects, first non-perfect matching of the bias source with the impedance of the Josephson sub arrays, which follow in decay times in the range of 100 ns. Second, the NI 5922 sampler use anti-aliasing filter for cutting off higher frequency contents (sampling theorem). Its decay time depend mainly on the sampling frequency of the digitizer and are in range of several microseconds.

It’s important to have an exact synchronisation of Josephson waveform, unknown AC waveform & sampler, therefore common trigger & clock signals must be used.

Reduction of the gain: - low input signal; measurements of pos. and neg. voltages, gain error on both sides

- phase difference → gain error

6.2 The biasing of the programmable Josephson array



Schematic binary sequence of the programmable Josephson voltage standard array with connected 50 Ohm bias sources.

According the rules of Kirchhoff:

1) $-U_1+I_1*R_{1}50+U_{J1}–I_2*R_{2}50–U_2 = 0;$
$I_1= I_{J1};$

2) $-U_2+I_2*R_{2}50+U_{J2}–I_3*R_{3}50–U_3 = 0;$
$I_2= I_{J2} –I_{J1};$

3) $-U_3+I_3*R_{3}50+U_{J3}–I_4*R_{4}50–U_4 = 0;$
$I_3= I_{J3} –I_{J2};$

4) $-U_4+I_4*R_{4}50+U_{J4}–I_5*R_{5}50–U_5 = 0;$
$I_4= I_{J4} –I_{J3}$

…

16) $-U_{16}+I_{16}*R_{16}50+U_{J16}–I_{17}*R_{17}50–U_{17} = 0;$
$I_{16}= I_{J16} –I_{J15}$

17) $-U_{17}+I_{17}*R_{17}50+U_{J17}–I_{18}*R_{18}50–U_{18} = 0;$
$I_{17}= I_{J17} –I_{J16}$

18) $-U_{18}+I_{18}*R_{18}50+U_{J18} +I_{J18}*R_{1\Omega} = 0;$
$I_{18}= I_{J18} –I_{J17}$

Development the formula to U_X:

$U_{18} = U_{J18} +(I_{J18} –I_{J17})*R_{18}50;$

$U_{17} = U_{J18} +U_{J17} +(I_{J17} –I_{J16})*R_{17}50;$

$U_{16} = U_{J18} +U_{J17} +U_{J16} +(I_{J16} –I_{J15})*R_{16}50 ;$

$U_{15} = U_{J18} +U_{J17} +U_{J16} +U_{J15} +(I_{J15} – I_{J14})*R_{15}50;$

$U_{14} = U_{J18} +U_{J17} +U_{J16} +U_{J15} +U_{J14} +(I_{J14} – I_{J13})*R_{14}50;$

$U_{13} = U_{J18} +U_{J17} +U_{J16} +U_{J15} +U_{J14} +U_{J13} +(I_{J13} –I_{J12})*R_{13}50;$

…

$U_1 = U_{J18} +U_{J17} +U_{J16} +U_{J15} +U_{J14} +U_{J13} + …….. +U_{J2} +U_{J1} +(I_{J1})*R_{1}50;$

At an operating frequency of 70 GHz the Josephon voltage standard circuit (JVSC) can generate quantised voltage levels in the range of −10 V to +10 V at intervals of about 140 µV according to equation 1. These discrete voltage levels are referred to Shapiro steps. To generate a certain Josephson voltage, or to set a certain N of equation 1, the different segment of the JVA arrays must be activated or not. This task is taken by several bias sources, to drive the JJA segments (sub arrays) with currents of $-I_B$, 0, or $+I_B$. If a sub array is driven by the positive bias current it generates the corresponding positive Josephson voltage and if the bias current is zero that sub array gives no contribution to the full array voltage.

The bias sources have an internal resistance of about 50 Ohm, identified by R_X50 (X corresponds to the number of the bias source), so the bias currents can be driven via a voltage with high speed. For generation of a certain voltage level the bias current I_B of each segment has to be determined, according the number of junctions in each sub array. In the following the bias currents of the sub array X are indicated by I_{JX}, which can be equal $+I_B$, $-I_B$ or 0.

By applying the rules of Kirchhoff we can found:

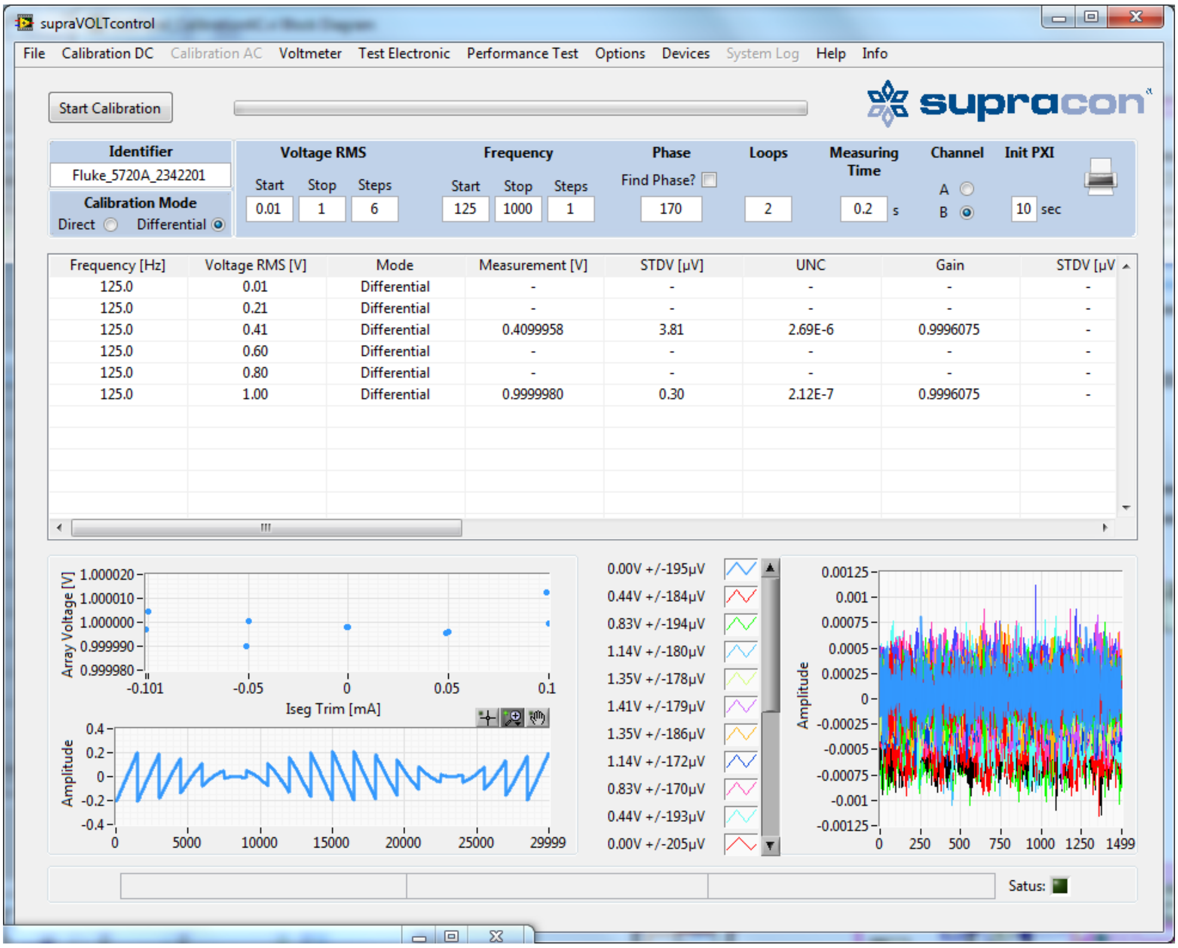
$U_{18} = U_{J18} + (I_{J18} - I_{J17}) * R_{18}50$
$U_{17} = U_{J18} + U_{J17} + (I_{J17} - I_{J16}) * R_{17}50$
$U_{16} = U_{J18} + U_{J17} + U_{J16} + (I_{J16} - I_{J15}) * R_{16}50$
$U_{15} = U_{J18} + U_{J17} + U_{J16} + U_{J15} + (I_{J15} - I_{J14}) * R_{15}50$
$U_{14} = U_{J18} + U_{J17} + U_{J16} + U_{J15} + U_{J14} + (I_{J14} - I_{J13}) * R_{14}50$
$U_{13} = U_{J18} + U_{J17} + U_{J16} + U_{J15} + U_{J14} + U_{J13} + (I_{J13} - I_{J12}) * R_{13}50$
…
$U_1 = U_{J18} + U_{J17} + U_{J16} + U_{J15} + U_{J14} + U_{J13} + \ldots\ldots + U_{J2} + U_{J1} + (I_{J1}) * R_1 50$

As an example, the Josephson voltage should be 1.16 mV. According the Josephson equation ($V_J = N*f/K_{J90} = 1.16$ mV) the number N must be 8 in this case. Therefore sub array no. 15 with 8 JJs should be driven with positive bias current ($I_{J15} = I_B$ -> $U_{J15} = 8*f/K_{J90}$), and the current of all other sub arrays should be zero ($I_{JX} = 0$ -> $U_{JX} = 0$ for $X \neq 15$). According the equations and with the parameters (R_X50=50 Ohm, f=70 GHz, U_{J15}=1.16mV, $I_{J15}=I_B$=3mA) the voltages of the bias sources have to be adjusted to:

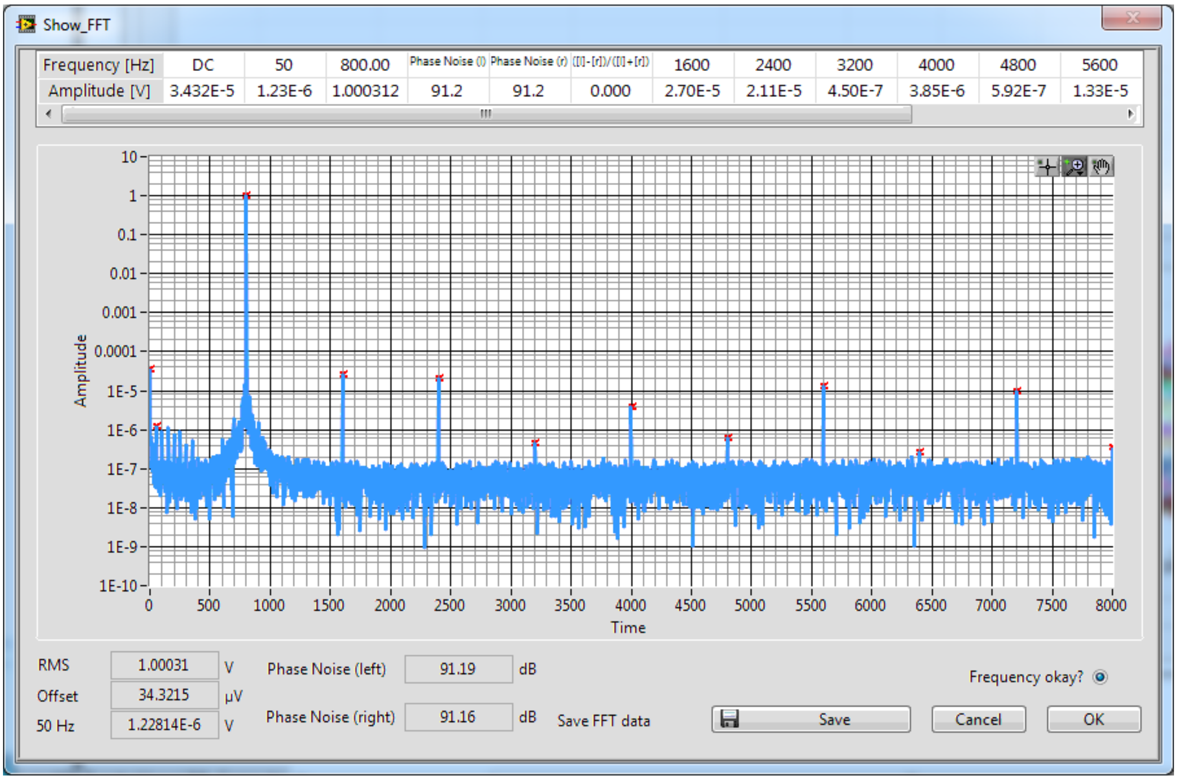
$U_{18} = 0$	~ 0
$U_{17} = 0$	~ 0
$U_{16} = -I_B * R_{16}50$	~ –150mV
$U_{15} = +8*f/K_{J90} + I_B * R_{15}50$	~ +1.16mV +150mV
$U_{14} = +8*f/K_{J90}$	~ +1.16mV
$U_{13} = +8*f/K_{J90}$	~ +1.16mV
…	
$U_1 = +8*f/K_{J90}$	~ +1.16mV
$U_{Josephson} = +8*f/K_{J90}$	~ +1.16mV

According to these equations each voltage between +/- 10 V can be programmed with an increment of 140 µV. With an additional timing and synchronisation of all bias sources also step wise approximated AC waveforms can be generated, which are used for calibration RMS voltages of sinus waves.

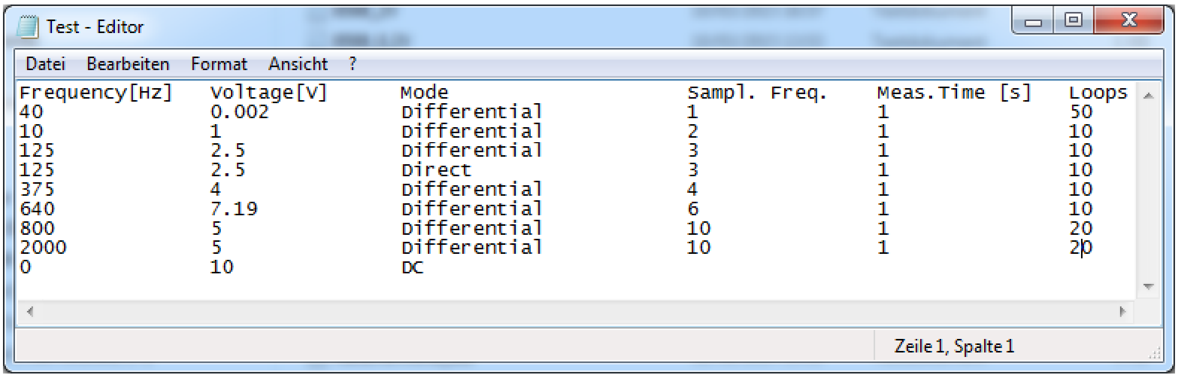
6.3 Calibration a Fluke 57XX calibrator



6.4 FFT



6.5 Load Calibration Values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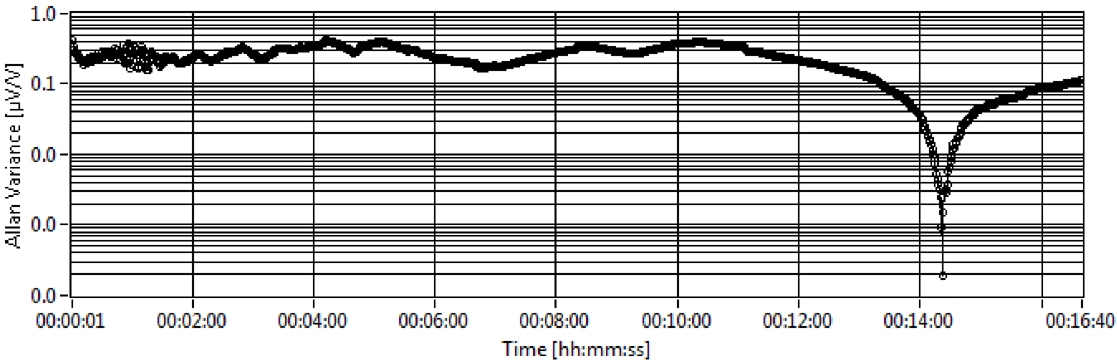
Datei Bearbeiten Format Ansicht ?

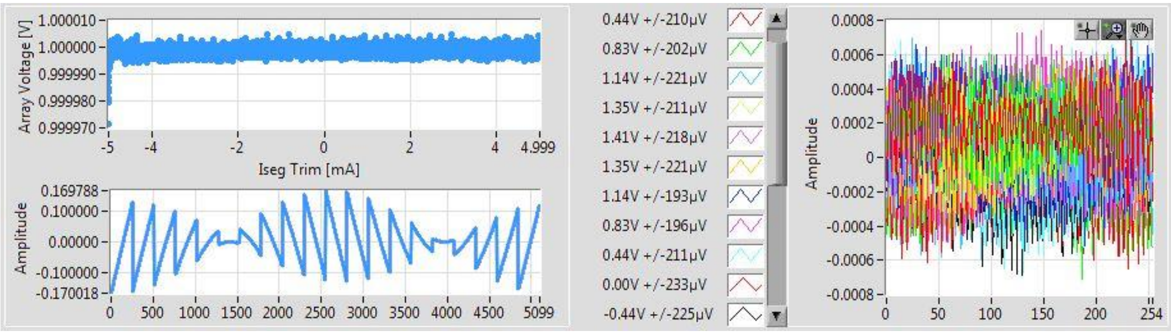
Frequency[Hz]	Voltage[V]	Mode	Sampl. Freq.	Meas.Time [s]	Loops
40	0.002	Differential	1	1	50
10	1	Differential	2	1	10
125	2.5	Differential	3	1	10
125	2.5	Direct	3	1	10
375	4	Differential	4	1	10
640	7.19	Differential	6	1	10
800	5	Differential	10	1	20
2000	5	Differential	10	1	20
0	10	DC			

Zeile 1, Spalte 1

6.6 Allan Deviation



6.7 Save Values



7 Instructions for handling liquid helium (Liquid Helium version)

The centre part of the AC Josephson system is a 10V programmable Josephson voltage standard array, which must be operated at a temperature of 4.2 K, the boiling temperature of liquid helium at normal barometric pressure. The programmable JJ array is mounted on a chip carrier which is installed in a cryoprobe. The cold head of the cryoprobe has to be immersed into a liquid helium Dewar. This chapter describes the safe handling of liquid helium and the cooling down and warming up cycles of the cryoprobe.

Follow the operating instructions of the manufacturer of the liquid helium Dewar, for instance Air Liquide, which you will find in the accompanying documentation.

7.1 Safety precautions

Before handling liquid helium:

1. Read the following guidelines.
2. Know and understand the properties and hazards associated with liquid helium.
3. Understand your liquid helium Dewar and its correct operation.

Liquid helium boils at a temperature of 4.2 K (-269°C). It is inert, colourless, odourless, non-corrosive, extremely cold, and non-flammable. Helium will not react with other elements or compounds under ordinary conditions. Since helium is non-corrosive, special construction materials are not required. However, the materials must be suitable for use at the extremely low temperatures.

Heating of the liquid helium leads to pressure increase and danger of the Dewar bursting. Spilled fluid is extremely cold and evaporates very quickly. Fluid contact to the skin leads to cold burns and fluid contact to the eyes leads to eye injuries. Helium gas can cause suffocation without preceding symptoms by displacing the oxygen of the air. Helium gas has a lower density than air, consequently it rises to the ceiling and spreads along the ceiling. There is also a **danger of skin adhesion to super cooled metal parts**. It is recommended to wear safety glasses, protective gloves and closed clothing when you have to carry out a refilling procedure.

To know what precautions to take is to recognize that at 4.2 K all other gases are solidified (the melting points of nitrogen, oxygen, and argon are 63.1 K, 54.4 K, and 83.8 K, respectively). Therefore, helium systems and Dewars must prevent the backflow of air as this constitutes a major safety hazard. **Dewars open to the atmosphere for prolonged periods can form "ice plugs" which help to contain the boil off which in turn can lead to overpressure and potential catastrophic failure (explosion)**. If you discover a Dewar which has been left open to the atmosphere for a period of time (e.g. via syphon entry port, helium recovery valve or bladder pressurisation valve):

1. Probe the inside of the Dewar with a helium dipstick in order to establish if it is clear and able to vent.

2. Report the event to your supervisor, senior technical staff or Departmental Safety Officer.

3. If the Dewar is blocked or partially blocked: Clear the area near the Dewar of all personnel and inform your supervisor immediately.

The extremely low temperatures associated with liquid helium can lead to condensation of the air's oxygen on the cold pipes. The condensed oxygen has the potential to drip down and combust spontaneously if it comes into contact with oil or fat. Also contact with flames (e.g. lighters or lit matches) can result in explosive combustion.
Overpressure in the Dewar due to faulty operation is an explosion hazard. The pressure must be reduced slowly by a slight opening of the discharge valve. High pressures within the Dewar can lead to a large increase of the boiling temperature of the liquid helium. Consequently, an abrupt tension release of the overheated liquid helium can result in a very high boil off and strong oscillations until the liquid gas has cooled down to its boiling temperature at atmospheric pressure again.
Cryogenic liquids kept in insulated Dewars remain at a constant temperature at their respective boiling points and will gradually evaporate. The very large increase in volume accompanying the vaporization of the liquid into gas and the subsequent process of warming up is approximately 1:700 for helium.

It is very important to consider the following safety precaution summary.

Liquid Helium Handling Golden Rules:

a. Always use and store in a well-ventilated area.
b. Always wear your eye protection.
c. Always wear your safety gloves.
d. Keep the liquid containers vertical at all times, avoid tilting the liquid helium Dewar.
e. Avoid mechanical or thermal shock.
f. Open valves slowly and be aware of gas noises.
g. Avoid splashing and use the minimum quantity required.
h. Never touch un-insulated pipes, parts or vessels.
i. Always transfer slowly.
j. Never leave a Dewar open to the atmosphere.
k. Never drop objects into the liquid helium.
l. Never accompany cryogenic liquid vessels in lifts.
m. Use protective goggles and protective gloves when handling cryogenic fluids, like liquid helium.
n. Avoid humidity intrusion into the liquid helium Dewar. Otherwise ice-formation inside the neck of the liquid helium Dewar is possible.

Finally imagine cryogenic liquids to be like "hot boiling water – only worse!"

Take extreme care at all times!

7.2 Instructions for cooling down and warming up the cryoprobe with the JJ array

Read the following instruction for cooling down and warming up the cryoprobe with the JJ array chip carefully. Be sure to understand the safety precautions of chapter

The cryoprobe can be kept continuously immersed in the 65 Liter Dewar for as long as about 15 days between refills, see last paragraph of chapter.

The contribution of the cryoprobe to the liquid helium boil off rate of a 65 Litre Dewar from Air Liquide is about 2.4 Litre per day. The intrinsic boil off rate of this Dewar without the cryoprobe is about 1.6 Litre per day. If the cryoprobe is immersed permanently in this liquid helium Dewar, starting with a full Dewar, measurements can be done over a period of about 15 days. If the cryoprobe is positioned over night in the topmost position, where the cryoprobe can not be moved any higher, then the measuring period can be extended up to about 20 days. The cryoprobe can be stationed at the topmost, the lowest or any other position by means of the variable clamp.

7.2.1 Preconditions

Release the BHK head (see Dewar manual of AIR LIQUIDE) of the liquid helium Dewar and insert the cryoprobe into the liquid helium Dewar only if:

Firstly no overpressure exists, see in Figure the differential pressure manometer (5) on the Dewar!
Secondly the gas discharge valve (4) of the Dewar is in the open position!

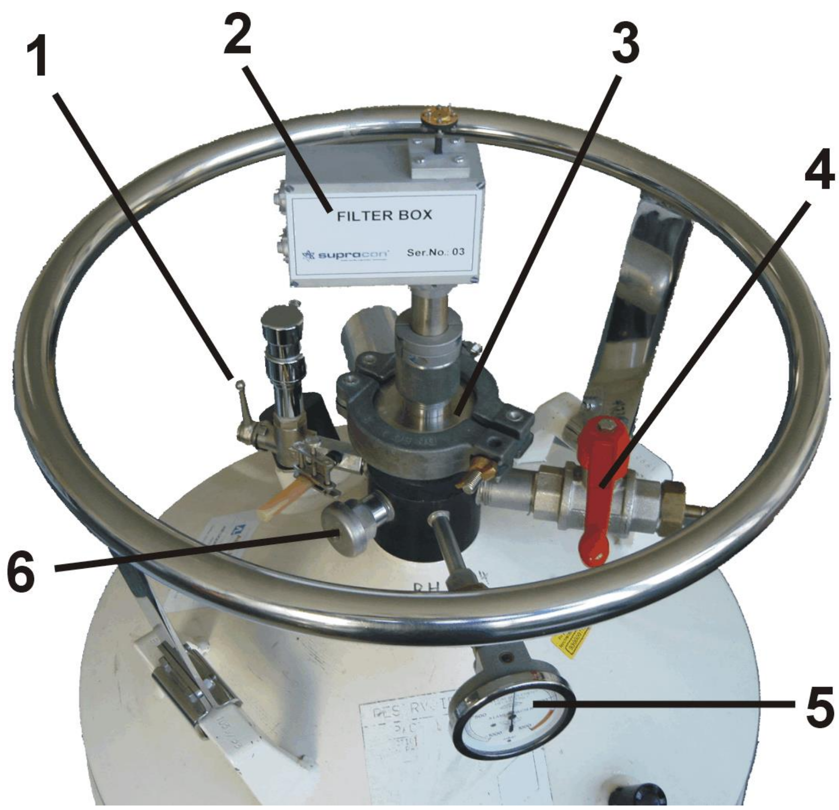


Figure 6 Helium Dewar: Top view of the liquid helium Dewar with the inserted cryoprobe.
1: Road transport relief valve (here in the open position), 2: filterbox of the cryoprobe, 3: ND50 sliding Dewar mount flange, 4: gas discharge valve (here in the closed position), 5: differential pressure barometer, avoid an overpressure of more than 50 mbar in the liquid helium Dewar, 6: safety valve set at 0.5 bar.

7.2.2 Cooling down cycle of the cryoprobe

Cool down the cryoprobe without the microwave electronics attached.
Avoid an overpressure of more than 50 mbar in the liquid helium Dewar during the cooling down cycle.
Slightly tip on the differential pressure barometer (**5** in Figure) with a finger in order to overcome the friction in it and to improve the measurement. Cool down slowly: Insert the cryoprobe in small steps into the liquid helium Dewar over a time of at least 40 minutes.
We advise the cooling down of the JJ array chip by inserting the cryoprobe in several 10 cm steps, with a pause at each position of about 5 minutes.

1. **Satisfy yourself that no overpressure exists in the Dewar.**
2. **Open the gas discharge valve (4) and open the road transport relief valve (1) of the Dewar**, see Figure .
3. Slide the ND50 sliding Dewar mount flange (**3** in Figure) of the cryoprobe down to the cryoperm shield and fix this position by means of the variable clamp.
4. Open the flange clamp and take out the BHK head of the liquid helium Dewar. Insert the cryoprobe in the Dewar at its highest position, fix the ND50 sliding Dewar mount flange with the flange clamp.
5. Close the gas discharge valve (4), the road transport relief valve (1) must be still open.
6. Move the cryoprobe about 10 cm down, fix it at this position with the variable clamp, and wait for about 5 min. Repeat this procedure until the cryoprobe is fully inserted in the liquid helium Dewar marked by the fixed clamp.
   Caution: If the overpressure is higher than 40 mbar keep the cryoprobe at this position, for at least 10 minutes and then continue.

7.2.3 Warming up cycle of the cryoprobe

Follow the instructions of chapter 7.2.2 in the reverse sequence.

1. Disconnect the 70 GHz microwave synthesizer from the cryoprobe top WR12 flange (use the attached hex wrench), and disconnect the power supply of the synthesizer.
2. Disconnect all 17 SMB cables at the cryoprobe.
3. Pull out the cryoprobe in 10 cm steps and wait at these positions for at least 5 minutes.
4. Leave the cryoprobe at its highest position if measurements are to undertaken with the same liquid helium Dewar.

If the liquid helium Dewar must be exchanged by a refilled Dewar then leave the cryoprobe at its highest position for about 30 minutes, to warm up almost completely.

Open the discharge valve (**4** in Figure), open the flange clamp, pull out the cryoprobe, insert the BHK head, fix it with the flange clamp, and close the gas discharge valve (**4** in Figure) of the Dewar.

Do not heat the cryoprobe during the warm up procedure! Warm up the cryoprobe slowly in order to reduce the formation of frost and water caused by melting frost. Heating of the cryoprobe causes worse problems than condensed water.

8 Contact

In the case of any technical problems with the system or if you have some questions please do not hesitate to contact us. We will do our best to help you.

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